CALETの軌道上観測性能と初期観測成果

CALET: In-flight Performance and Preliminary Results

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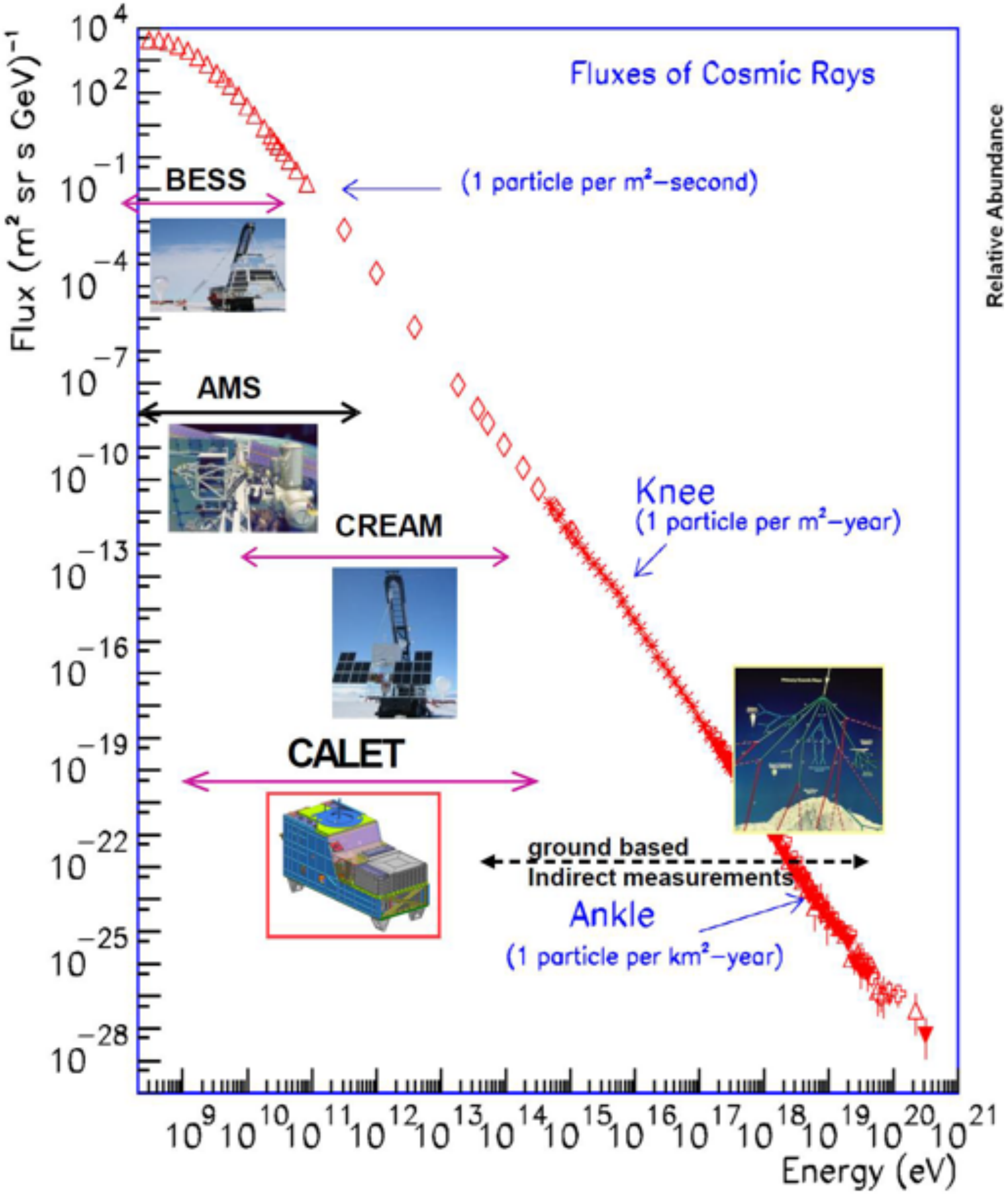
CALETによる宇宙線観測



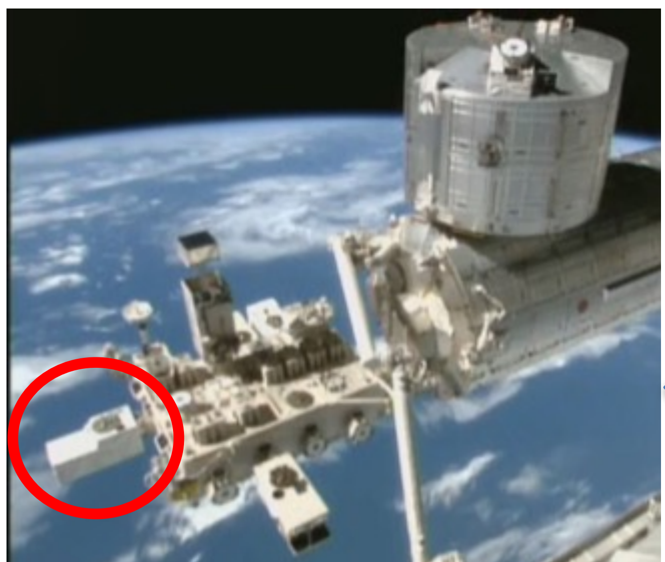
- 宇宙空間における最も高いエネルギー領域での宇宙線直接測定
- 国際宇宙ステーションにおける大型装置による5年間の長期観測により、世界最高レベルの宇宙線観測を実施
- 高精度な位置分解能と非常に厚いカロリメータ(30 X_0)により、高エネルギー領域での観測を実施
- 電子観測に最適化することにより、1GeV–20 TeV領域での電子観測を高エネルギー分解能で達成
  ⇨ 近傍加速源、暗黒物質の探索
- 原子核成分の観測を数10GeV–1PeVの領域で実施
  ⇨ 宇宙線加速・伝播機構の解明
- 安定的運用により突発現象の観測
  ⇨ REP, 重力波の同時観測

CALET is now on the ISS since Aug.25, 2015

① **August 19th**: Launch of the Japanese H2-B rocket by JAXA at 20:50:49 (JST)

② **August 24th:**
The HTV-5 Transfer Vehicle (HTV-5) is grabbed by the ISS robotic arm.

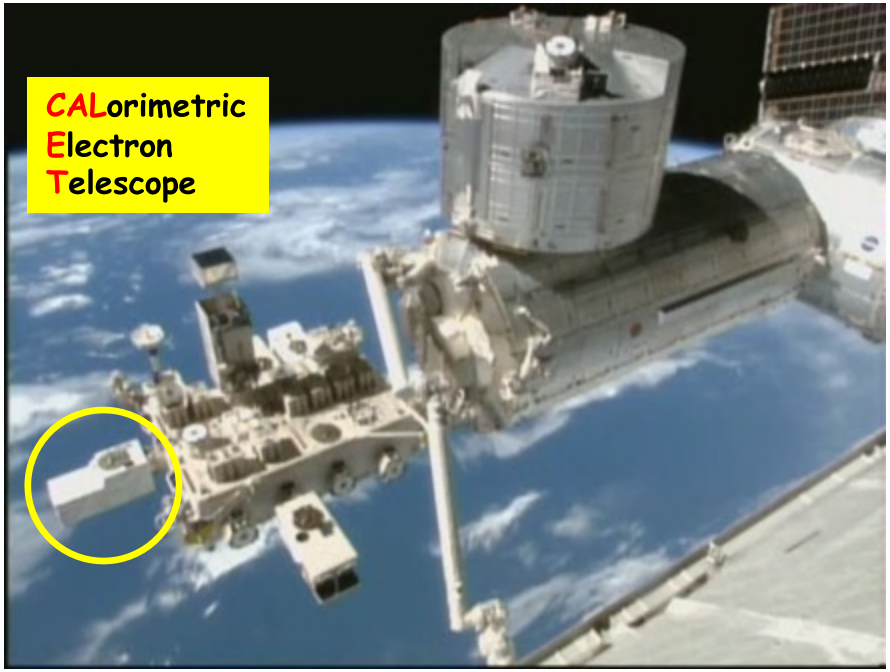
③ **August 24th:**
The HTV-5 docks to the ISS at 2:28 (JST).



④ **August 25th:**
CALET is emplaced on port #9 of the JEM-EF and data communication with the payload is established.

CALETによる科学観測

カロリメータ（CALET/CAL）
- 電子: 1 GeV – 20 TeV
- ガンマ線: 1 GeV – 10 TeV
  (ガンマ線バースト: > 1 GeV)
- 陽子・原子核:
  数10GeV – 1,000 TeV
- 超重核:
  Rigidity Cut 以上のエネルギー



ガンマ線バーストモニタ（CGBM）
- 軟ガンマ線：100 keV – 20 MeV
- 硬X線 ：7 keV – 1 MeV（山岡）

観測目的	観測対象
宇宙線近傍加速源の同定	TeV領域における電子エネルギースペクトル
暗黒物質の探索	電子・ガンマ線の100 GeV–10 TeV領域におけるスペクトルの”異常”
宇宙線の起源と加速機構の解明	電子及び陽子・原子核の精密なエネルギースペクトル、超重核のフラックス
宇宙線銀河内伝播過程の解明	二次核/一次核(B/C)比のエネルギー依存性
太陽磁気圏の研究	低エネルギー(<10GeV)電子フラックスの長・短期変動
ガンマ線バーストの研究	7 keV – 20 MeV領域でのX線・ガンマ線のバースト現象

これまでの観測結果

銀河宇宙線の
統一的理解

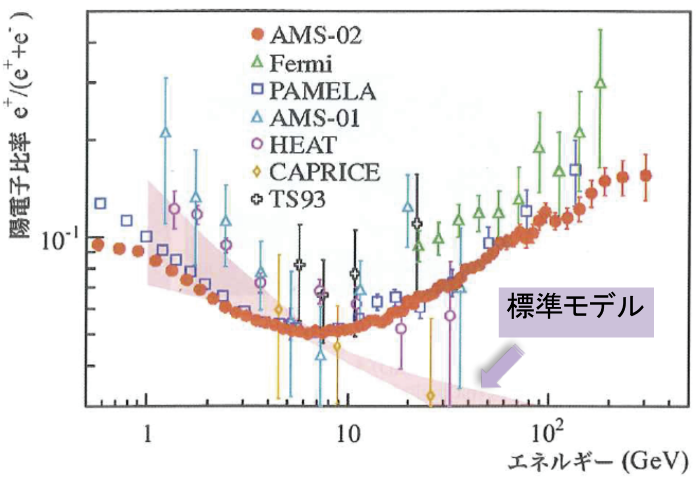
⇕

銀河内宇宙線加速・伝播の“標準モデル”

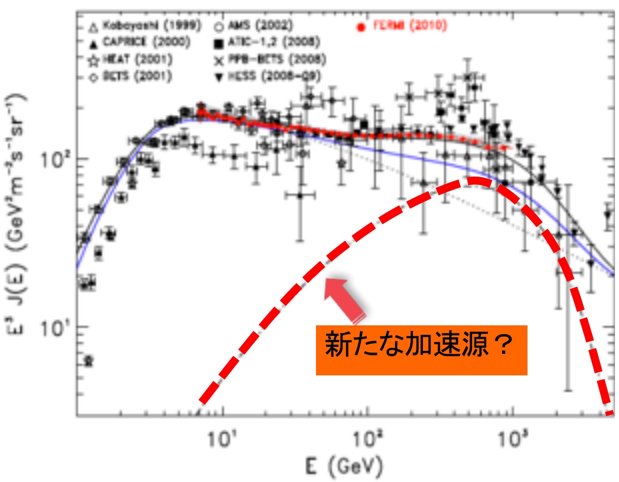
- □ 超新星残骸における衝撃波加速機構
  - 冪型エネルギースペクトル (d*N*/d*E* $\propto$ $E^{-\gamma}$)
  - 電荷に比例した加速限界(E_c ～100 *Z* TeV)
- □ 銀河磁場による拡散的伝播過程（+電子・陽電子エネルギー損失）
  - 陽子・原子核成分のエネルギースペクトルの軟化 (~$E^{-\gamma-\alpha}$)
    銀河磁場からの漏れだしのエネルギー依存性（Leaky Box Model ）
  - 二次成分比（e^+/e^-, B/Cなど）のエネルギー依存性（$\propto E^{-\delta}$）

最近の観測による数100GeV領域における“標準モデル”と矛盾する現象

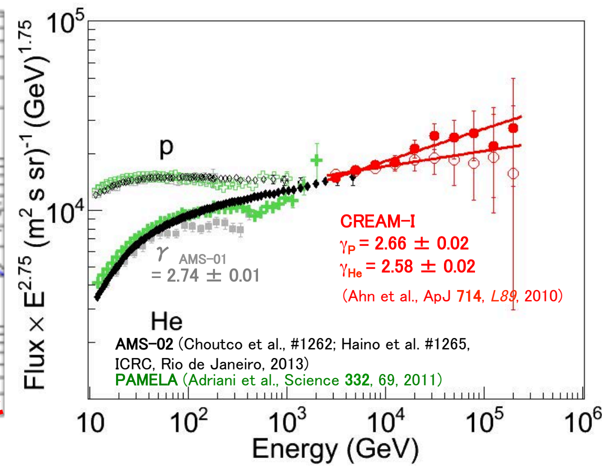
陽電子比の“増大”



電子＋陽電子成分の“過剰”



陽子、ヘリウムスペクトルの“硬化”



高エネルギー領域における新たな電子＋陽電子加速源の存在

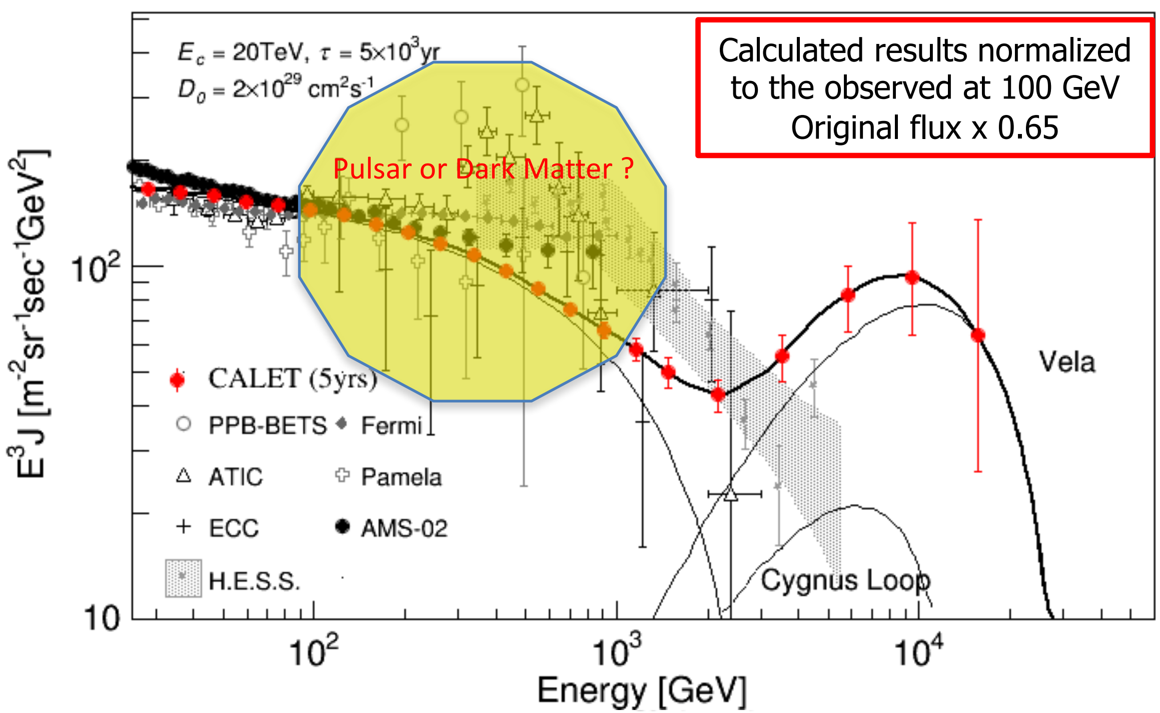
陽子・原子核成分の未知の
加速機構or伝播機構の存在

CALET Main Target: Identification of Electron Sources

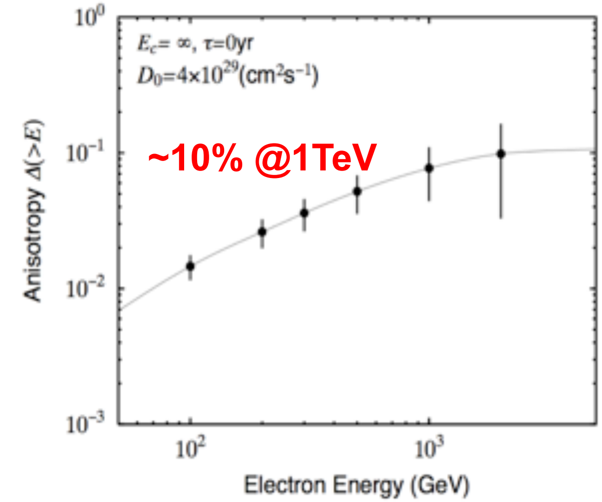
Some nearby sources, e.g. Vela SNR, might have unique signatures
in the electron energy spectrum in the TeV region (Kobayashi et al. ApJ 2004)

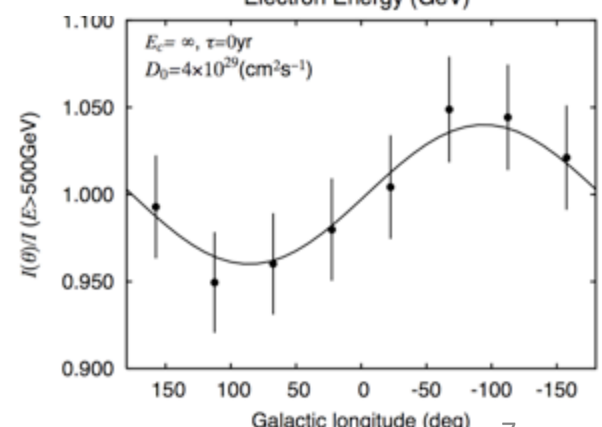
Expected flux
for 5 year mission
assuming E^{-3}

> 10 GeV	~ 2.7 x 10^7
>100 GeV	~ 2.0 x 10^5
>1000 GeV	~ 1.0 x 10^3



Expected Anisotropy
from Vela SNR



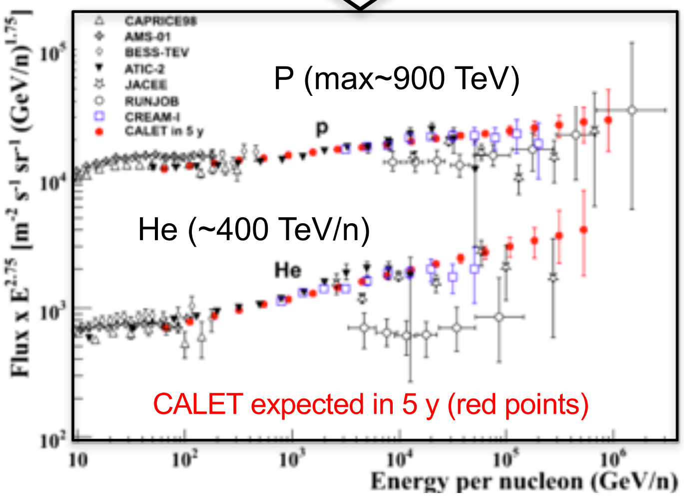


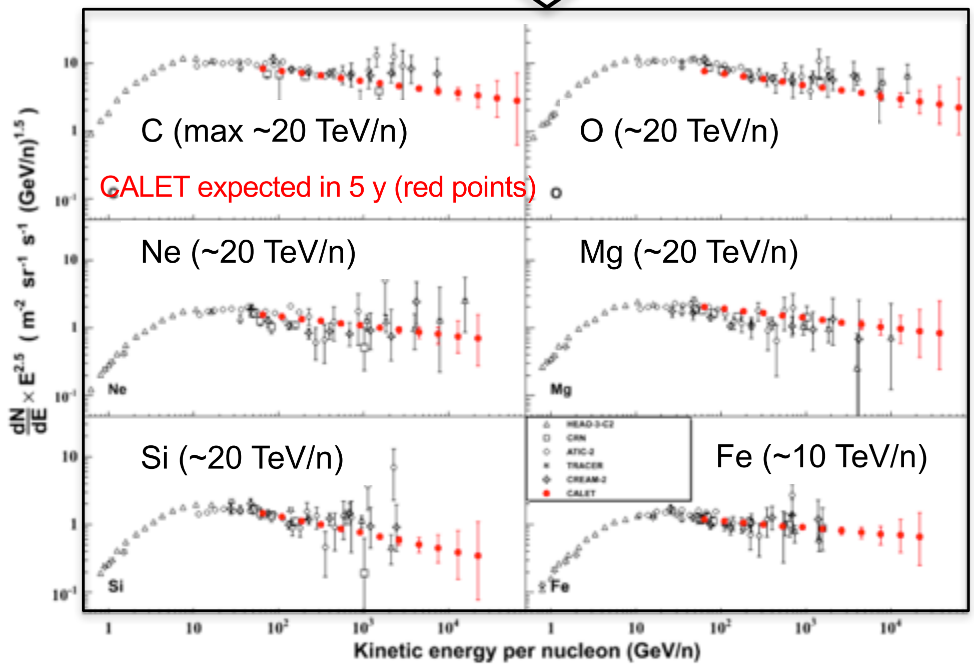
► Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET

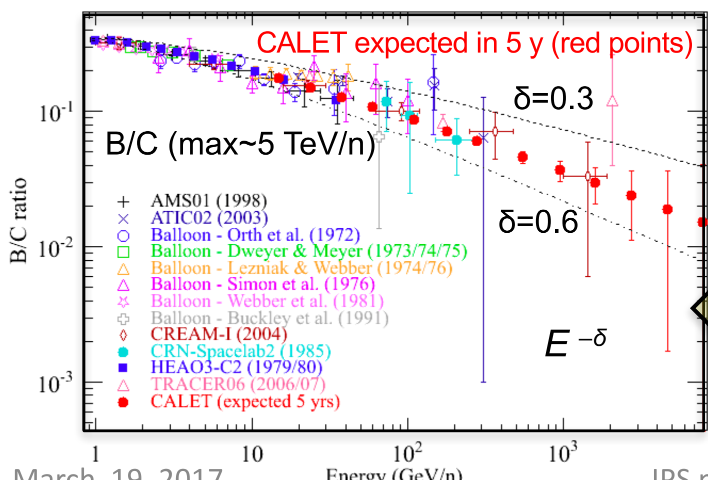
Measurements of Cosmic Nuclei Spectra with CALET

- Hardening in the p and He at 200 GV observed by PAMELA
- p and He spectra have different slopes in the multi TeV region (CREAM)
- Acceleration limit by SNR shock wave around 100 TeV/Z ?

- All primary heavy nuclei spectra well fitted to single power-laws with similar spectral index (CREAM, TRACER)
- However hint of a hardening from a combined fit to all nuclei spectra (CREAM)

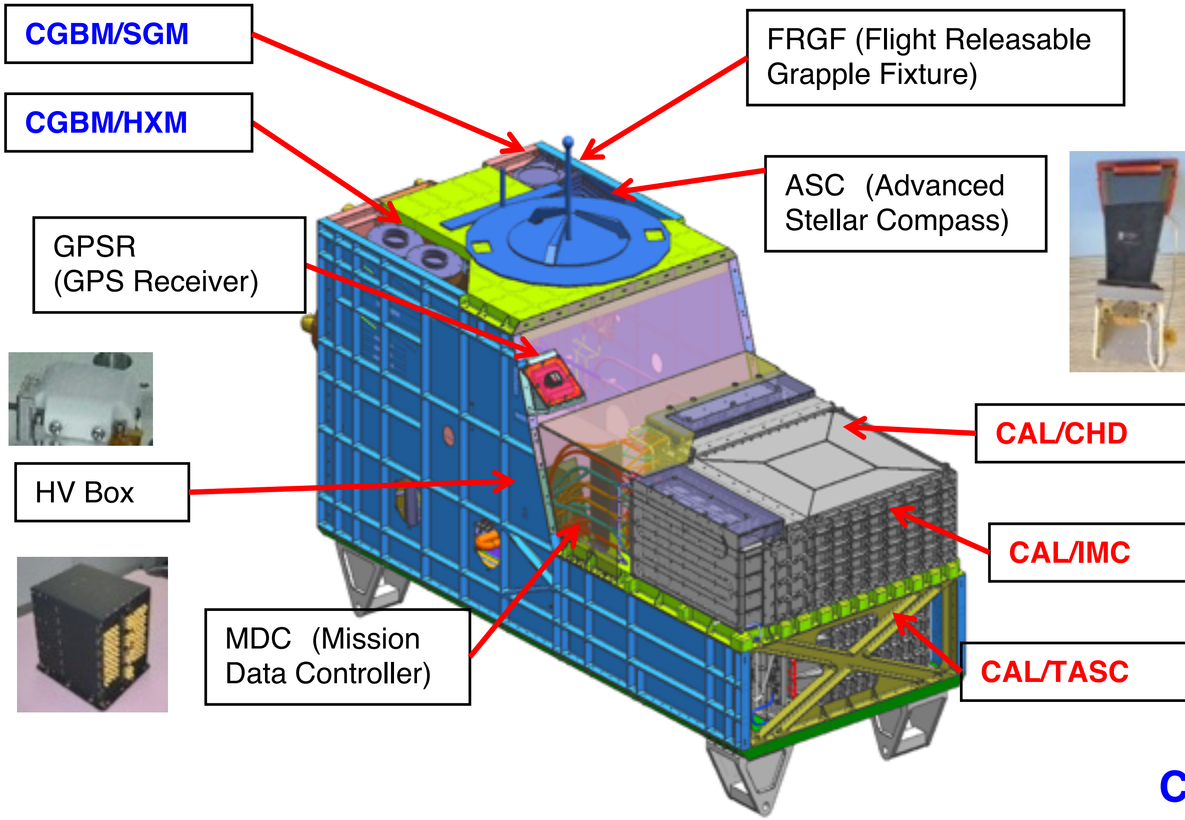




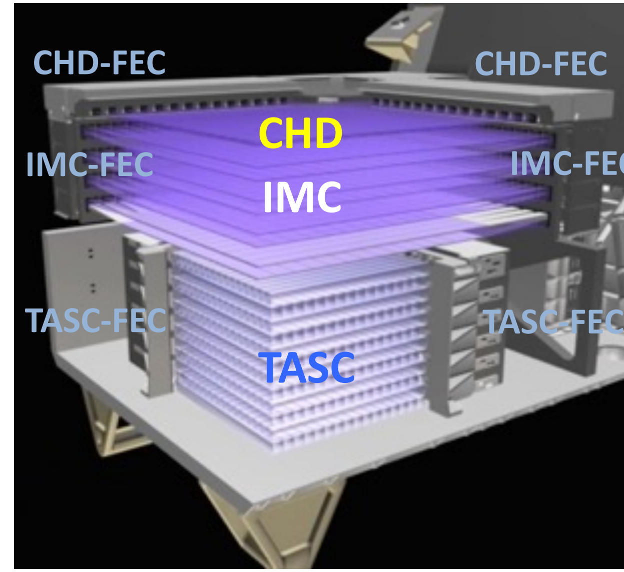


- At high energy (> 10 GeV/n) the B/C ratio measures the energy dependence of the escape path-length, $\sim E^{-\delta}$, of CRs from the Galaxy
- Data below 100 GeV/n indicate δ~0.6. At high energy the ratio is flatten out (δ~0.33)

CALET System Overview



CALORIMETER (CHD/IMC/TASC)



- Mass: 612.8 kg
- JEM Standard Payload Size

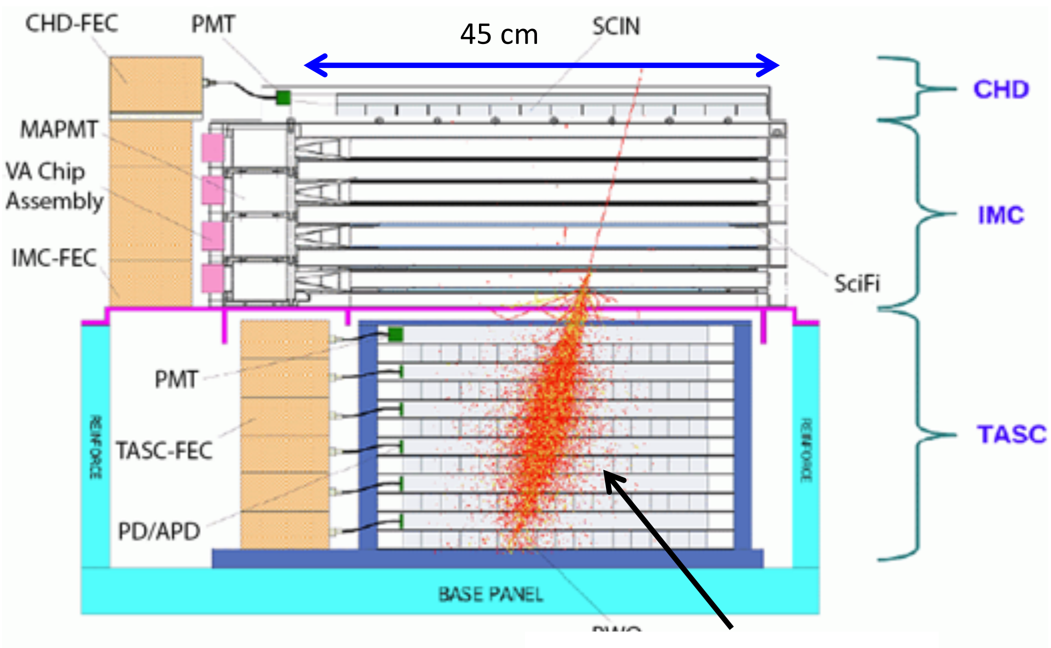
  1850mm(L) × 800mm(W) × 1000mm(H)
- Power Consumption: 507 W (max)
- Telemetry:

  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CGBM (CALET Gamma-ray Burst Monitor)

CALET: Instrument Overview

Field of view: ~ 45 degrees (from the zenith)
Geometrical Factor: ~ 0.12 m^2sr (for electrons)



1 TeV electron shower

Unique features of CALET

A dedicated charge detector + multiple dE/dx track sampling in the IMC allow to identify individual nuclear species (Δz~0.15-0.35e).

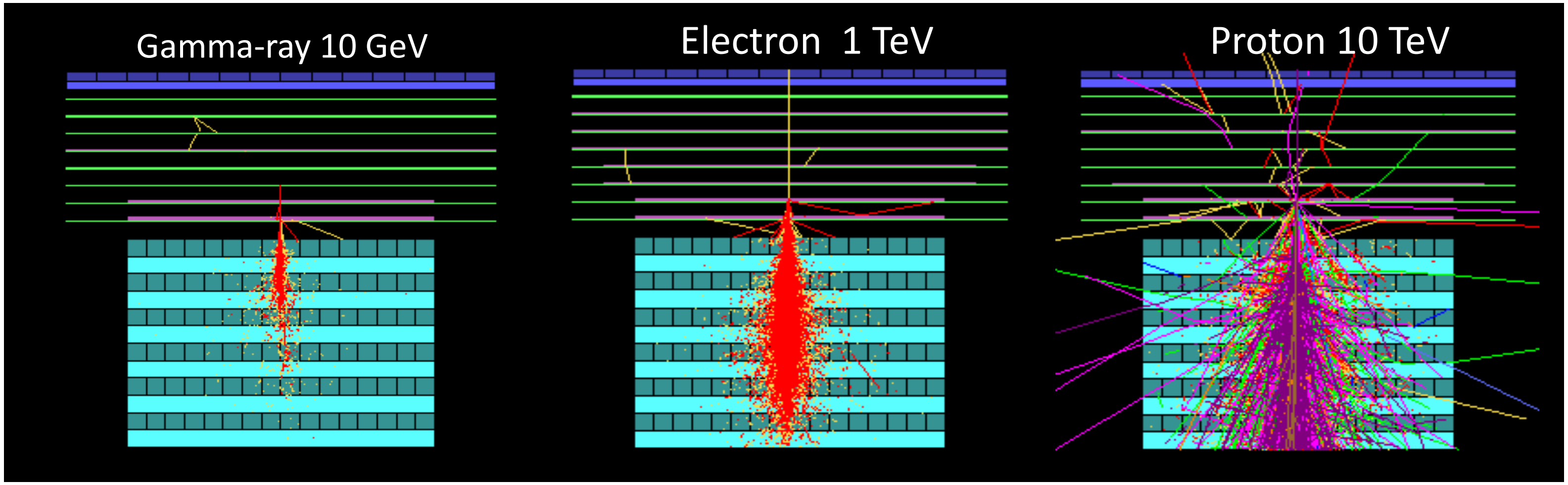
Thick(~30 X_0), fully active calorimeter allows measurements well into the TeV energy region with excellent energy resolution (~2-3%)

High granularity imaging pre-shower calorimeter accurately identify the arrival direction of incident particles (~0.2°) and the starting point of electro-magnetic showers.

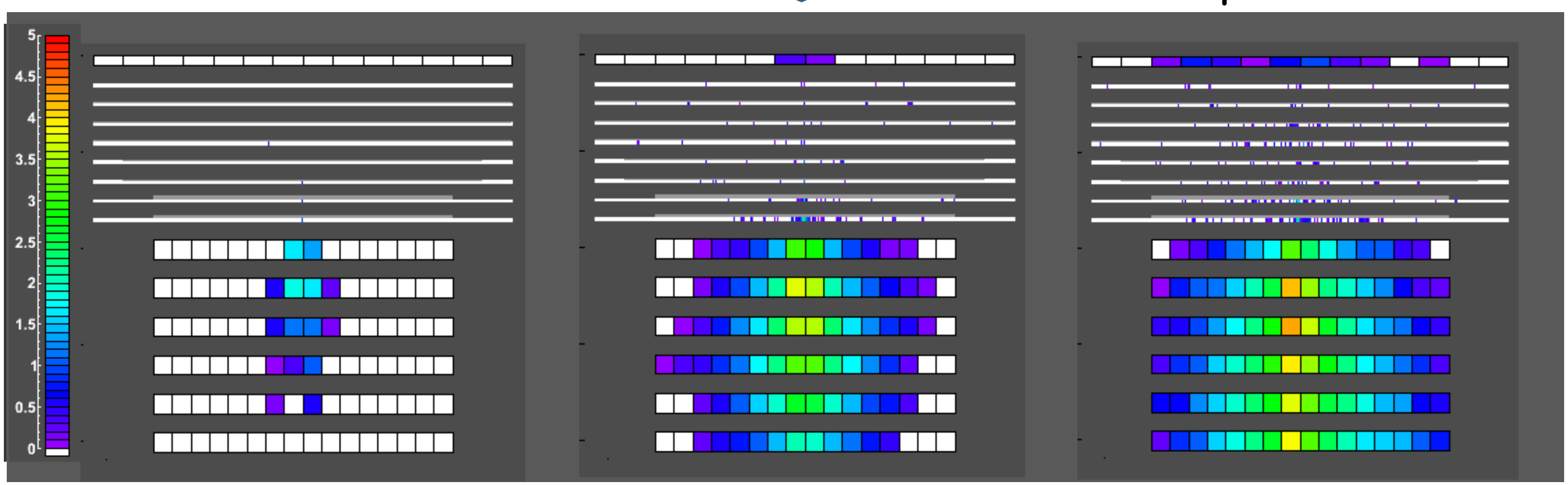
Combined, they powerfully separate electrons from the abundant protons: rejection power ~10^5.

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z=1-40)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	**Plastic Scintillator : 14 × 1 layer (x,y)** Unit Size: 32mm x 10mm x 450mm	**SciFi : 448 x 8 layers (x,y) = 7168** Unit size: $1mm^2$ x 448 mm **Total thickness of Tungsten: 3 X_0**	**PWO log: 16 x 6 layers (x,y)= 192** Unit size: 19mm x 20mm x 326mm **Total Thickness of PWO: 27 X_0**
Readout	**PMT+CSA**	**64 -anode PMT(HPK) + ASIC**	**APD/PD+CSA** PMT+CSA (for Trigger)@top layer

シミュレーション計算による粒子識別の概念



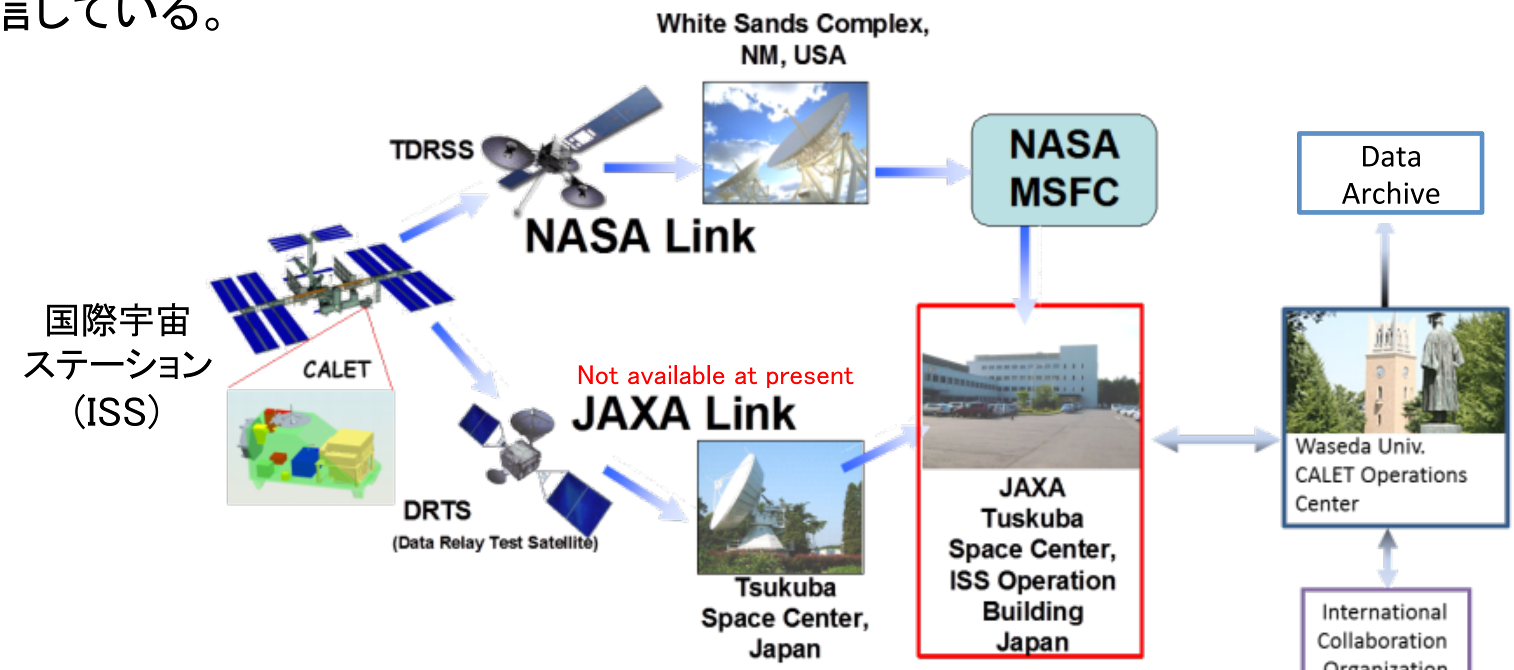
In Detector Space



非常に厚い(30 r.l) カロリメータ(IMC+TASC)によるシャワー画像の可視化技術により、電子選別に必要な陽子除去性能 を達成する。

CALETのデータフローとサイエンス運用概念

NASAリンクの低速・中速系によるリアルタイムデータ及び欠損補完データ(Level0)を、つくば宇宙センターを経由してWaseda CALET Operations Center (WCOC) で受信している。



WCOCでは2種類のデータを受信

<u>リアルタイムデータ</u>

- ISSから送出後数秒以内に受信

<u>解析用生データ(Level0データ)</u>

- 1時間に1回受信
- 時系列補正, 欠損補完済

筑波宇宙センターにおいて
CALET地上運用設備を構築し、主に装置の安全性の監視を行う
軌道上CALETとの直接のインタフェースを有し、データ受信・コマンド送信を行う.

早稲田大学にWaseda CALET Operations Center (WCOC)を構築し
ミッション運用として科学観測状況の監視とオペレーションを行う

CALETの統一的運用を担っている

Overview of Trigger Modes for CALET

High Energy Shower Trigger (HE)

- High energy electrons (10GeV ～20TeV)
- High energy gamma rays (10GeV ～10TeV)
- Nuclei (a few10GeV～1000TeV)

Low Energy Shower Trigger (LE)

- Low energy electron at high latitude (1GeV ～10GeV)
- GeV gamma-rays originated from GRB (1GeV ～)
- Ultra heavy nuclei (combined with heavy mode)

Single Trigger (Single)

- For detector calibration : penetrating particles (mainly non-interacting protons and heliums)

(*) In addition to above 3 trigger modes, heavy modes are defined for each of the above trigger mode. They are omitted here for simple explanation.

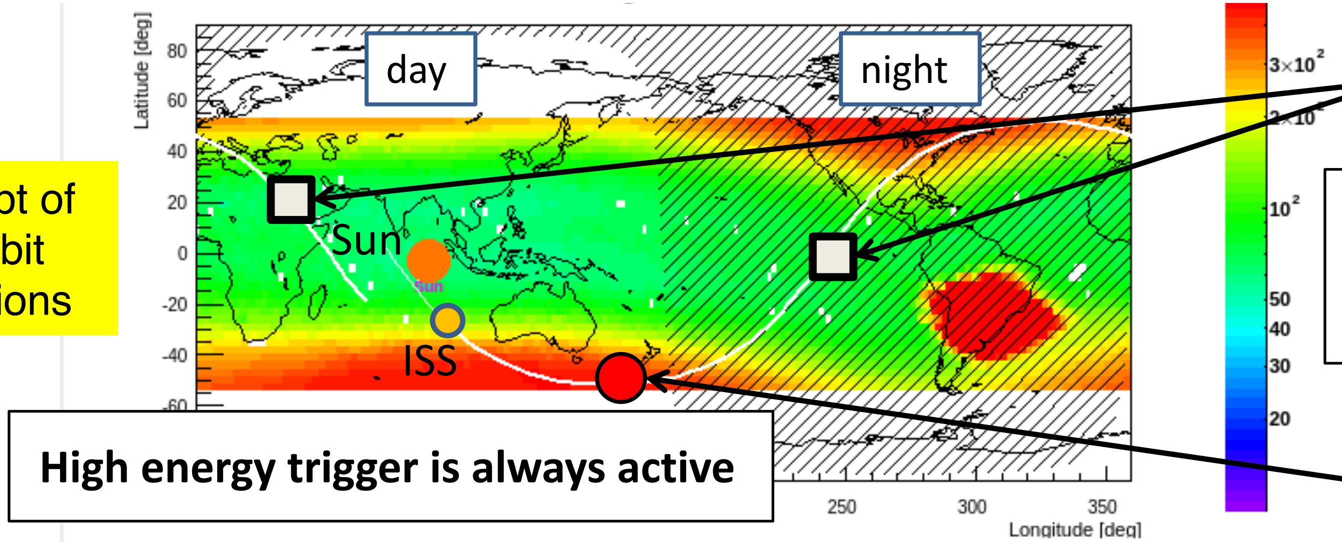
Auto Trigger (Pedestal/Test Pulse)

- For calibration:
  - ADC offset measurement (Pedestal)
  - FEC's response measurement (Test pulse)

ISS Orbit and CALET On-orbit Operations

ISS orbit: inclination 51.6 degree, ~400 km

Concept of on-orbit operations

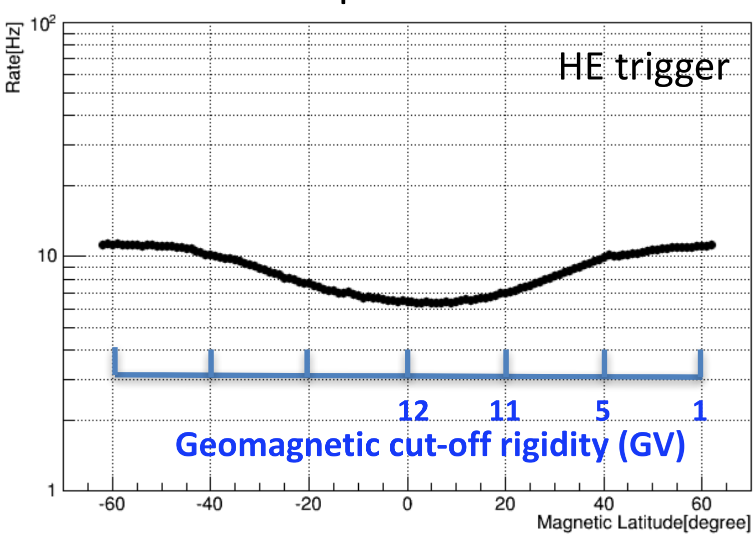


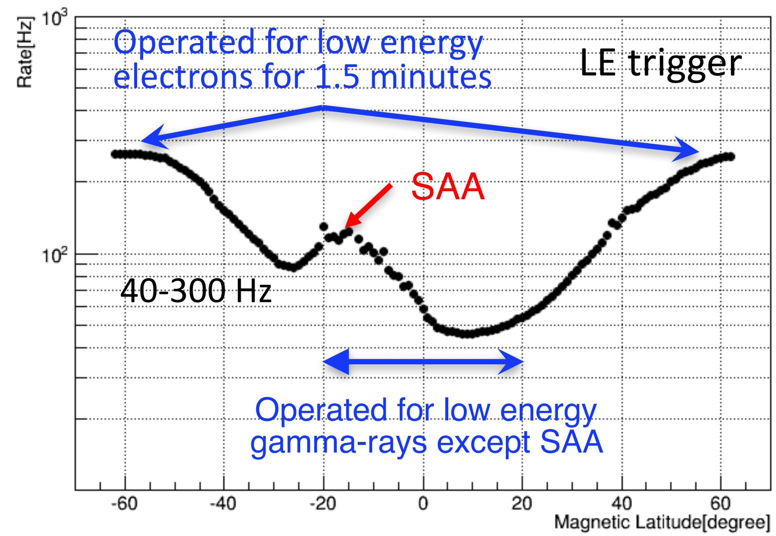
Pedestal data acquisition

Schedule file: sequence of time and command

Low energy electron shower data acquisition

Dependence of the count rate on geomagnetic latitude





Intrinsic Advantage of the CALET Instrument :

EM Shower Energy Measurement =TASC Energy Sum × “Small” Correction

- Active and thick calorimeter absorbs most of the electromagnetic energy (~95%) up to the TeV region
  - Fine energy resolution of ~ 2 %
  - Capability of measuring shower energy from 1GeV to 1000 TeV in 6 order of magnitude !
- In principle, energy measurement with very small systematic error is possible.
- Needs to obtain the ADC unit to energy conversion factor and to calibrate the whole dynamic range channel by channel

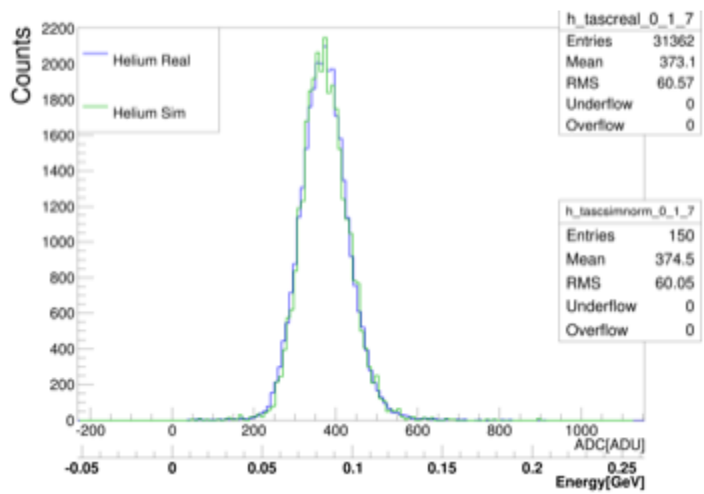
On orbit : Energy conversion factor using “MIP” of p or He

- Position and temperature dependence
- Latitude dependence due to rigidity cutoff

On ground: Linearity measurements for the whole dynamic range

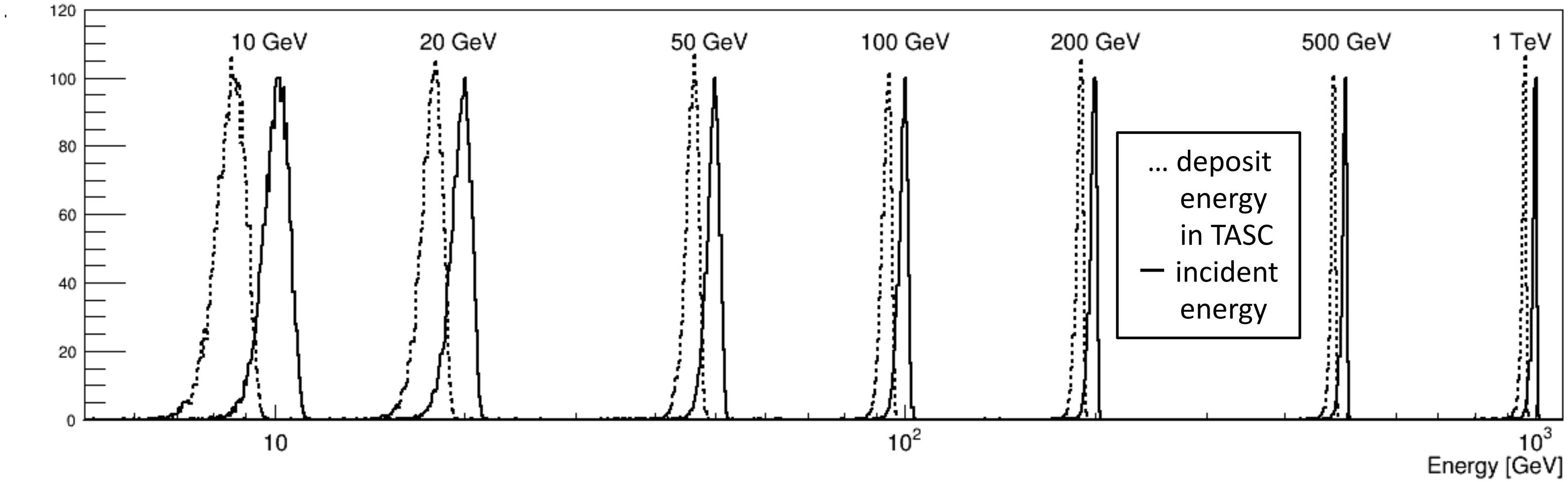
- CHD/IMC – Charge injection
- TASC – UV Laser irradiation (end-to-end)

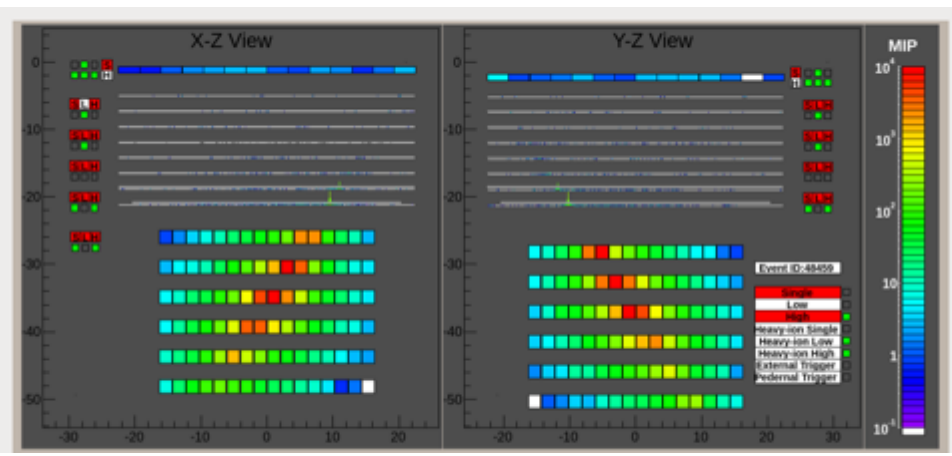
“MIP” peak in PWO: Obs. vs. MC



Energy Reconstruction for Electromagnetic Showers

Comparison of deposit energy in TASC （ΔE) with incident energy (E_0) by simulation

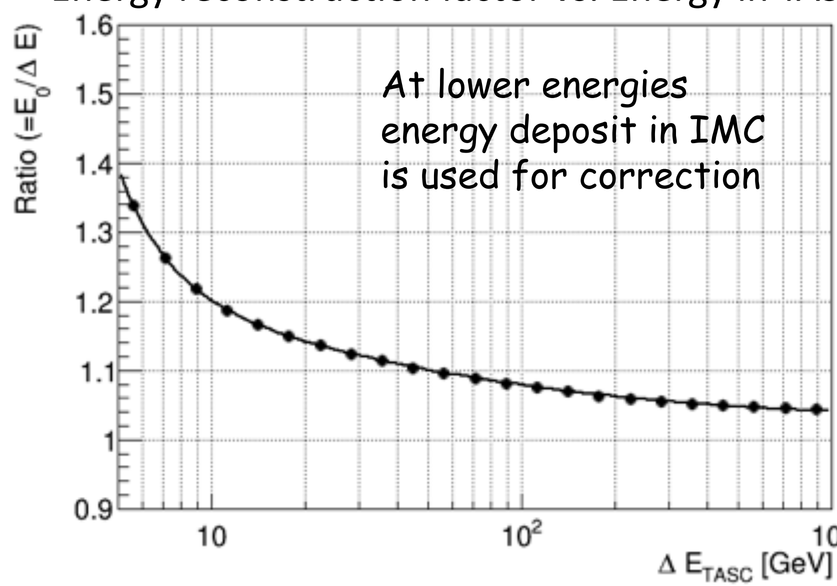




4 TeV electron candidate (well contained)

⇒ very small leakage (~ a few %)

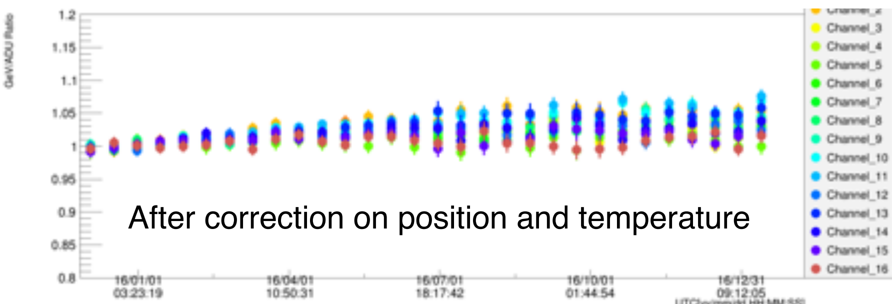
Energy reconstruction factor vs. Energy in TASC



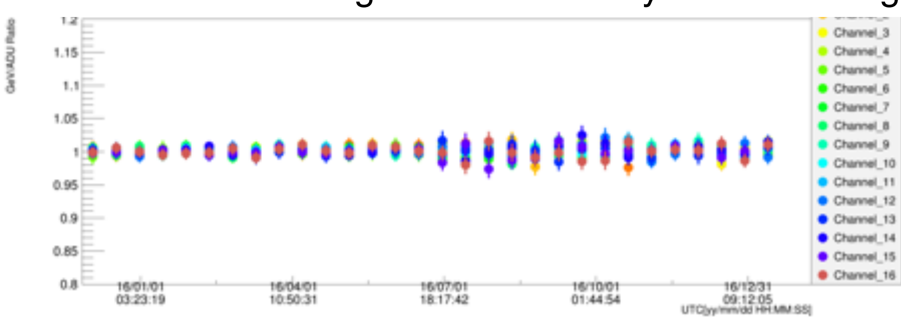
Long Term Stability of MIP Values with Correction on Position and Temperature

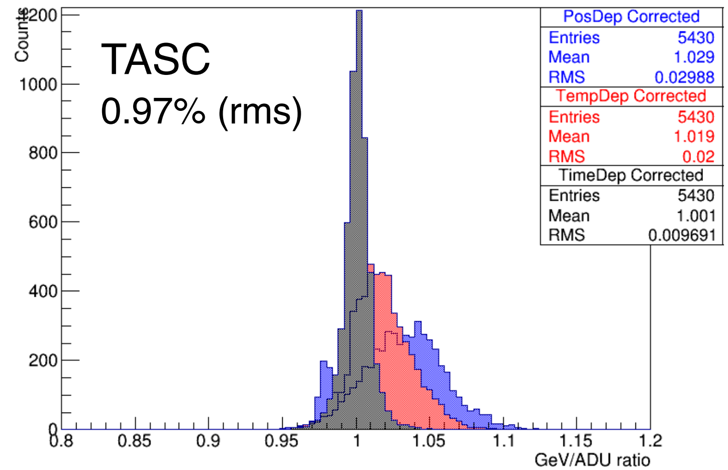
By applying the corrections on POSITION(3.0%) and TEMPERATURE(2.0%) (variables in time), the long term stability is corrected by function fitting and confirmed to be 0.97% (TASC) and 0.55% (CHD)

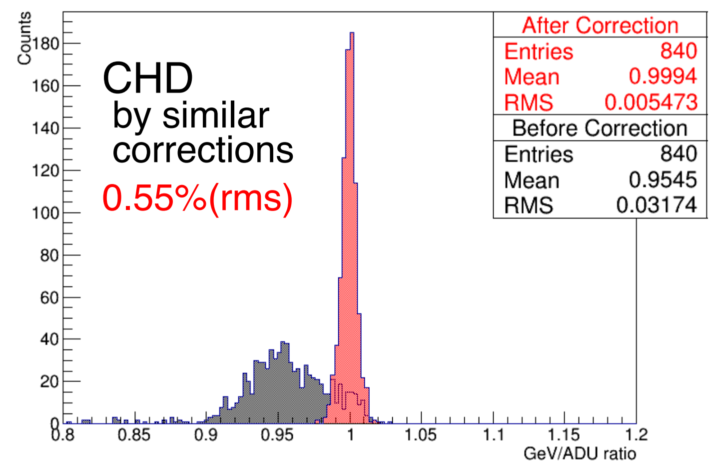
An example of long term variation of MIP value for 2015.12-2017.1 (TASC-Y6)



Correction of long term variation by function fitting

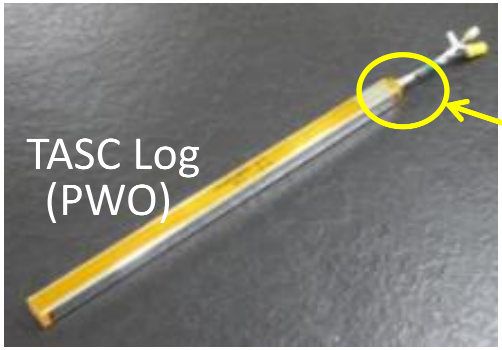


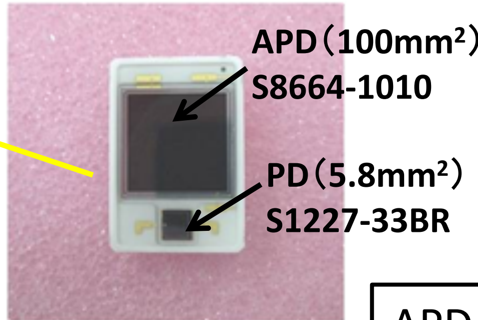


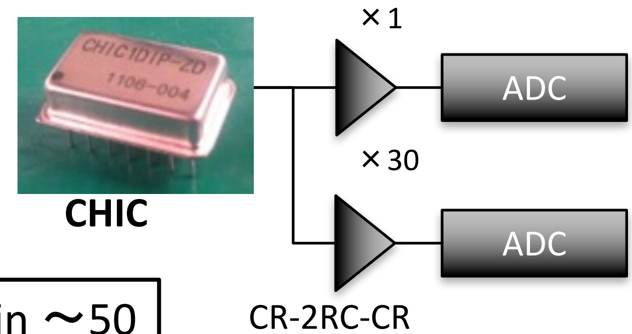


Corrections are carefully updated time by time

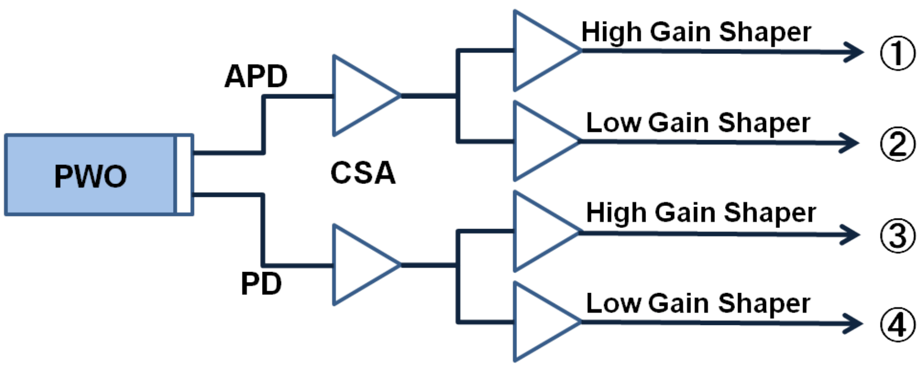
Energy Calibration in Dynamic Range of 1-10^6 MIP in TASC





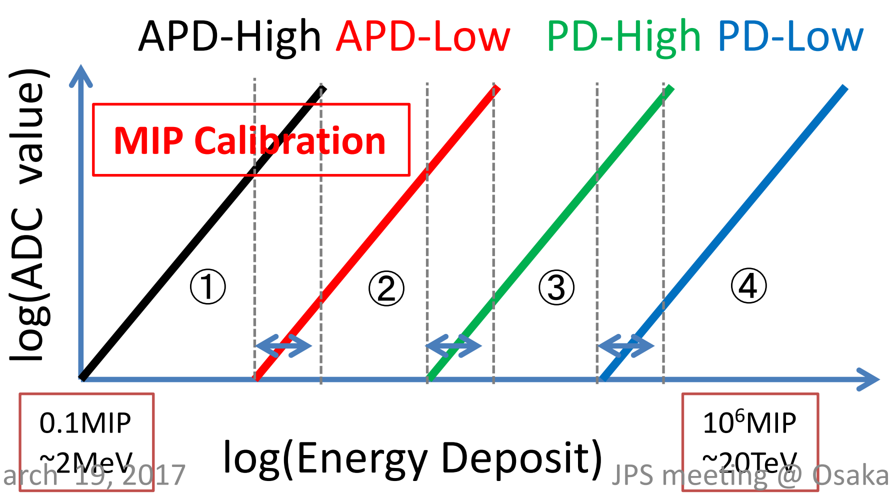


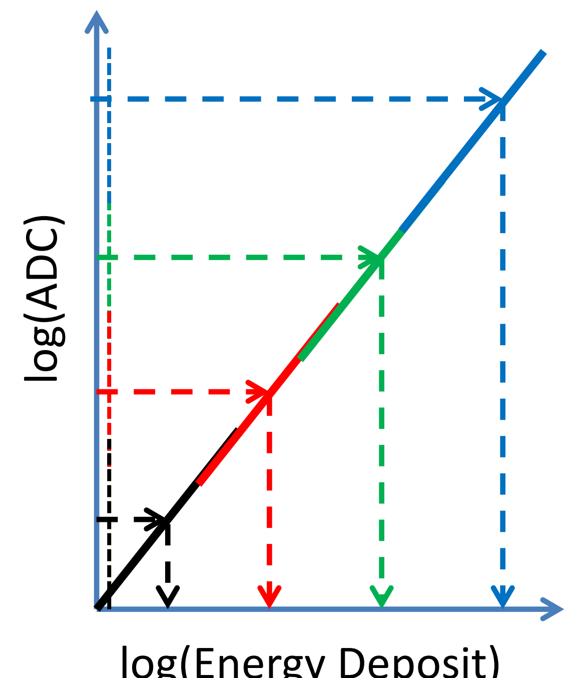
APD gain ～50



Calibrating full range (6 order of magnitude) is quite a challenge !

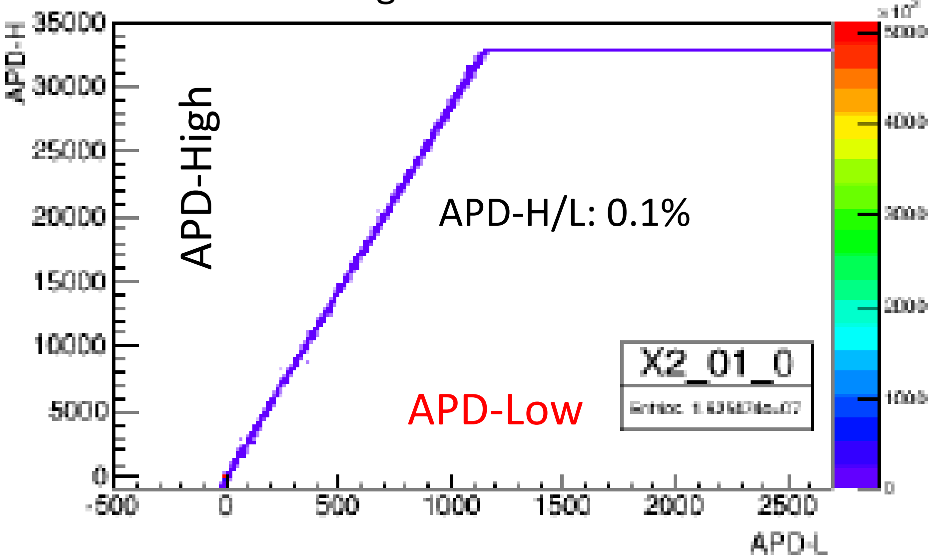
Gain Ratio Calibration Using UV Pulse Laser



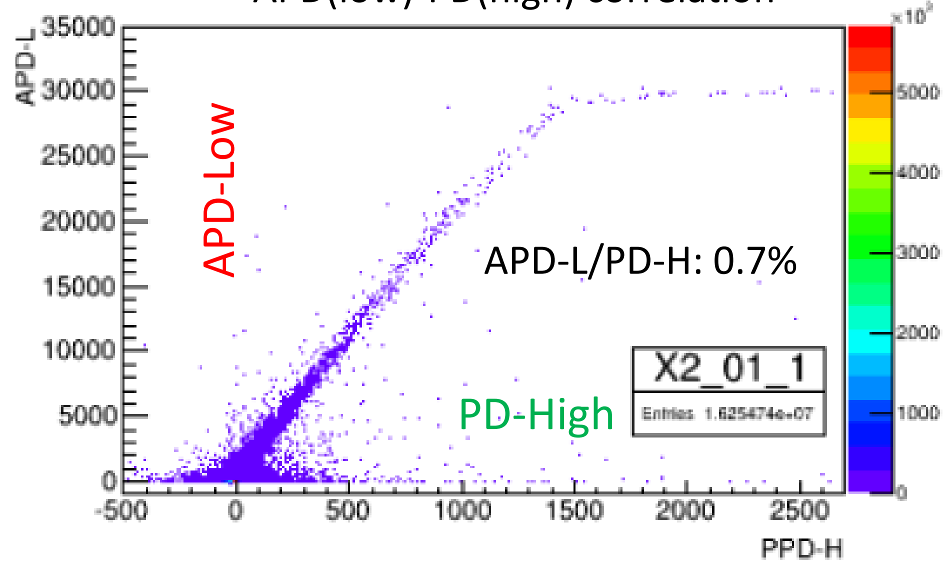


Correlation between Adjacent Gain Range for In-flight Data

APD high-low correlation



APD(low)-PD(high) correlation

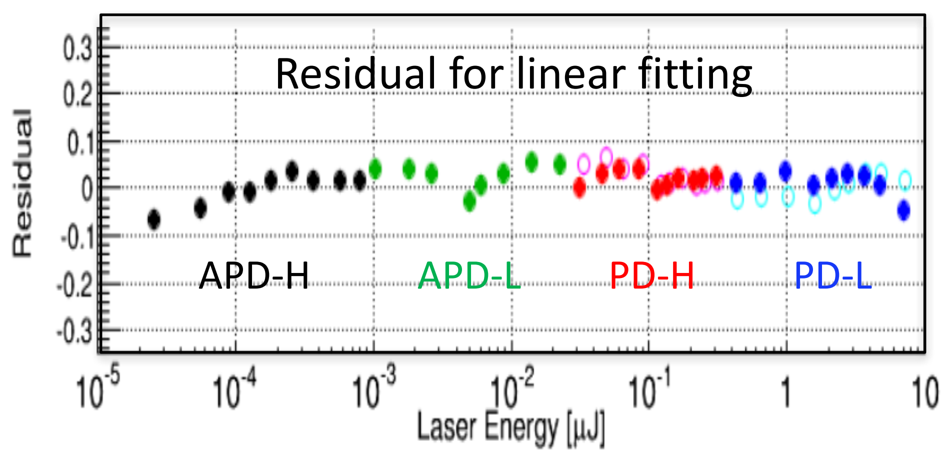


The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel . The linearity has been calibrated by using UV laser irradiation on ground :

1) The linearity is confirmed in the range of 1.4-2.5 %.

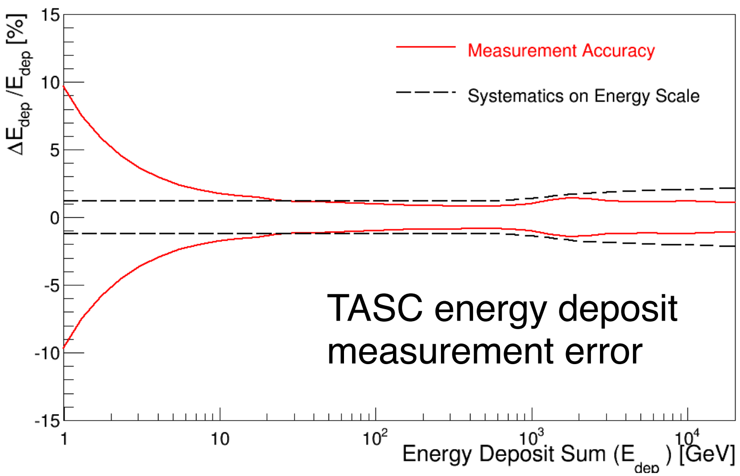
2) The whole dynamic range is confirmed to cover from 1 MIP to 10^6 MIPs.

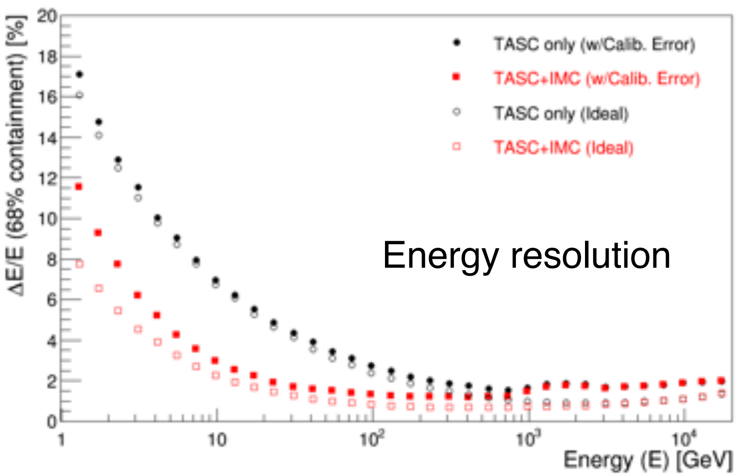
On-ground UV laser test for linearity



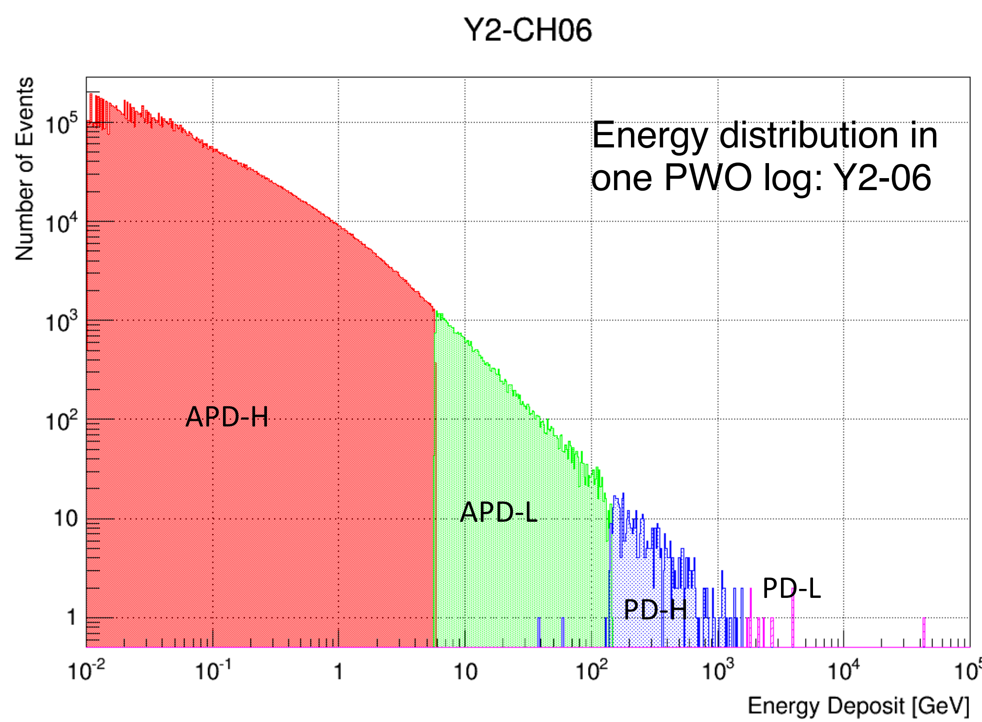
Energy Measurement by Adopting the In-flight Calibrations

Expected performance of energy measurement using TASC by simulations in which the in-flight calibration errors are included.





Confirmation of range connection accuracy using the observed events:
The different four ranges are smoothly connected from 1 MIP (~0.1GeV for He) to over 10^3 GeV in one PWO log.



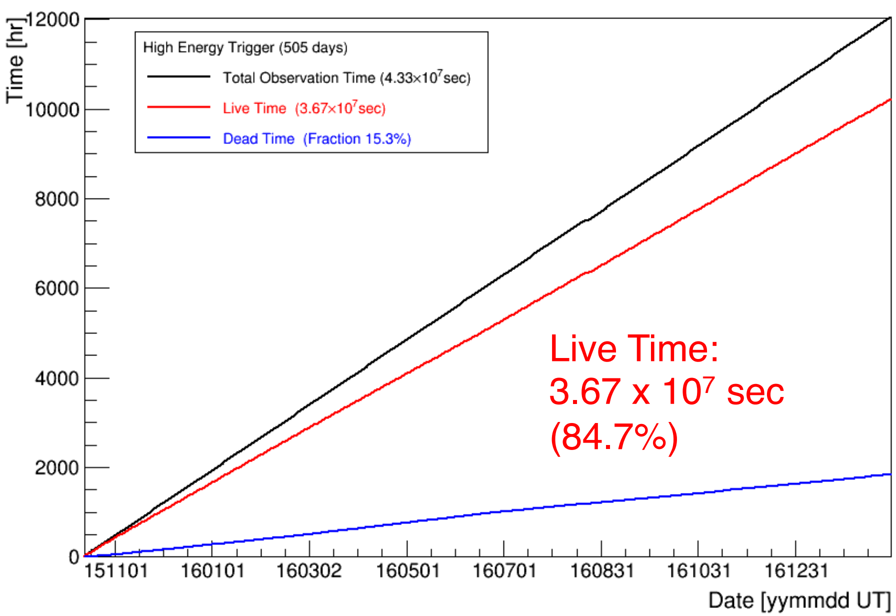
*) Y.Asaoka et al., Astroparticle Physics (in press)
高橋他、18aK21-3

Observation by High Energy Trigger(>10GeV)

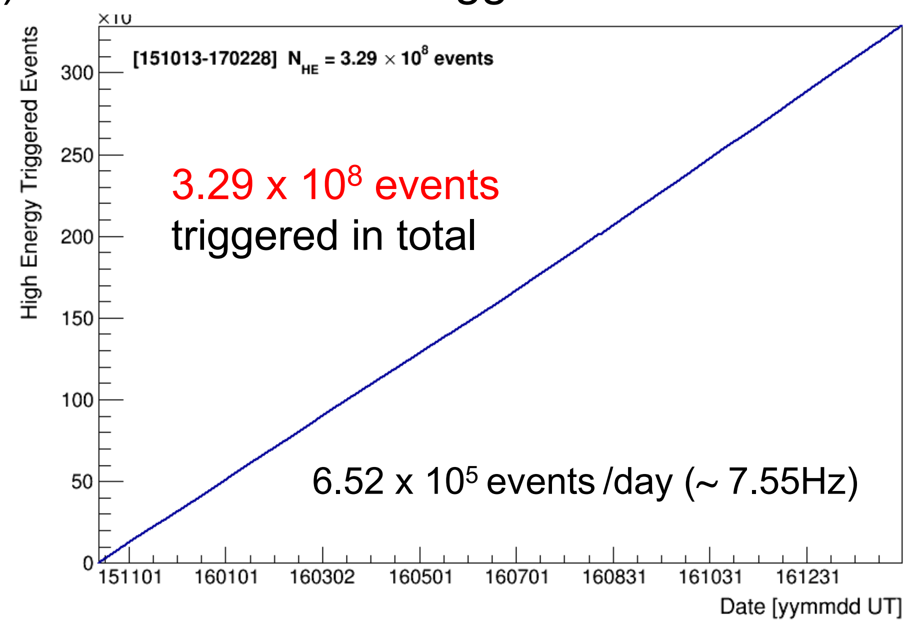
Observation by High Energy Trigger for 505 days :
Oct. 13, 2015 – Feb.28, 2017

- The exposure, $S\Omega T$, has reached to ~44 m^2 sr day by continuous observation.
- Total number of the triggered events is ~ 329 million with a live time of 84.7 %.

Accumulated observation time (live, dead)

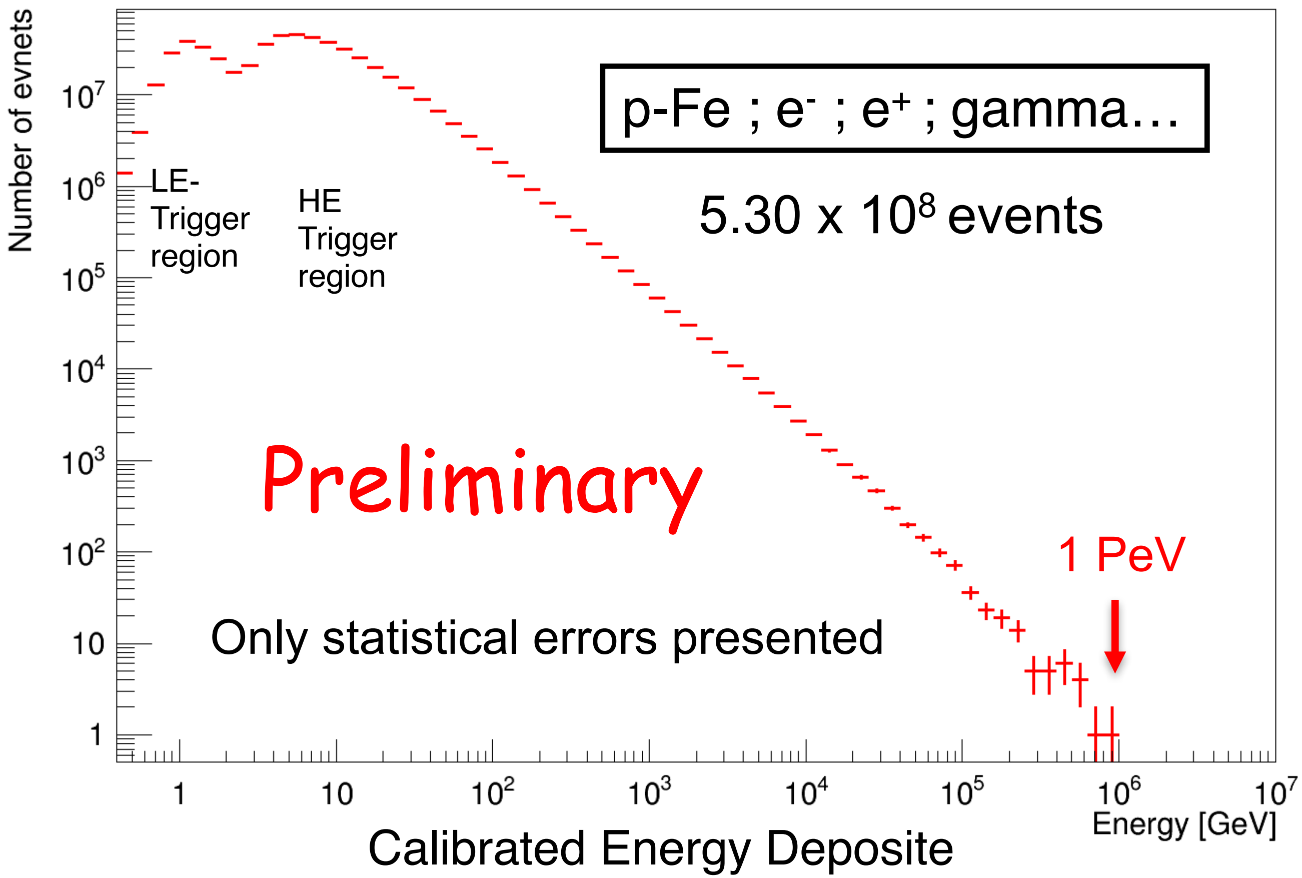


Accumulated triggered event number



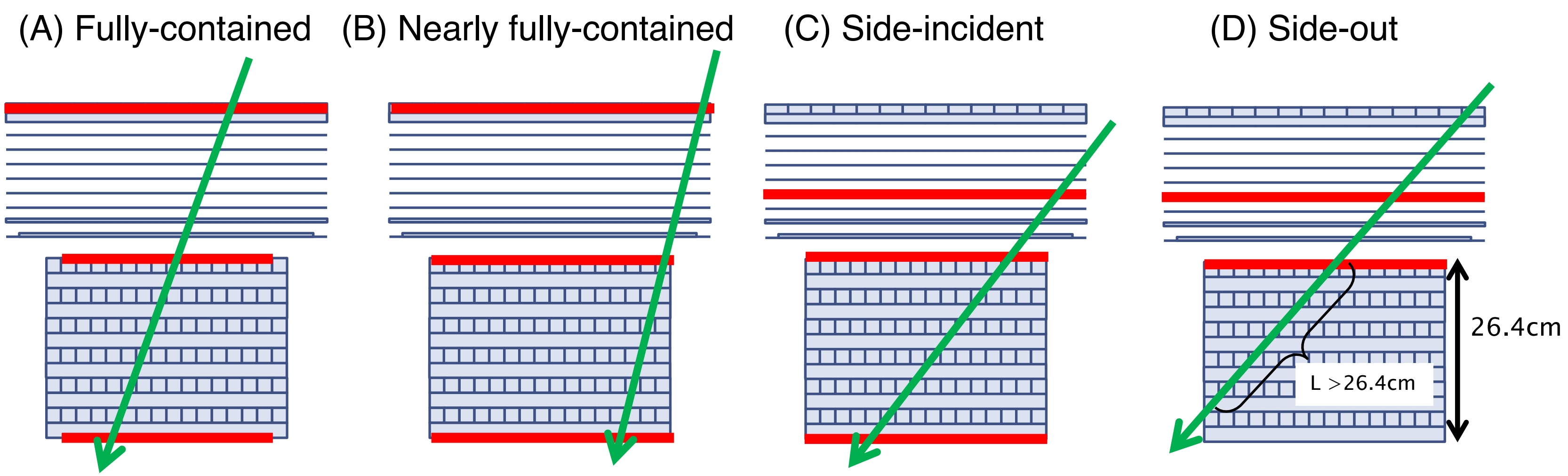
Energy Deposit Distribution of All Triggered-Events by Observation for 505 days

Distribution of deposit energies in TASC observed in 2015.10.13—2017.02.28



The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

Topological Condition for Data Analysis



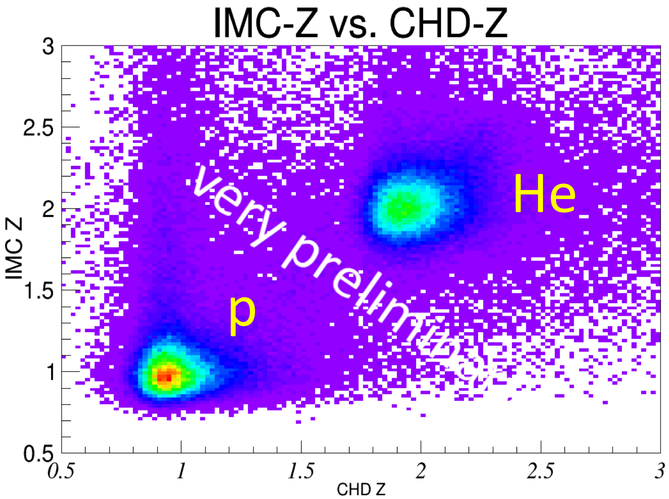
☆ Red layers must be passed by shower axis with additional condition

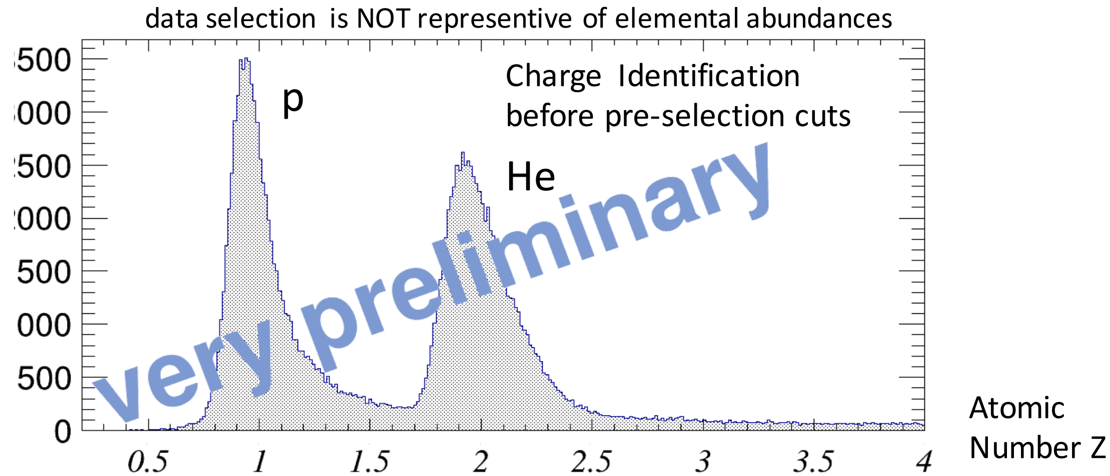
<u>Topological Cut in the Data Analysis</u>

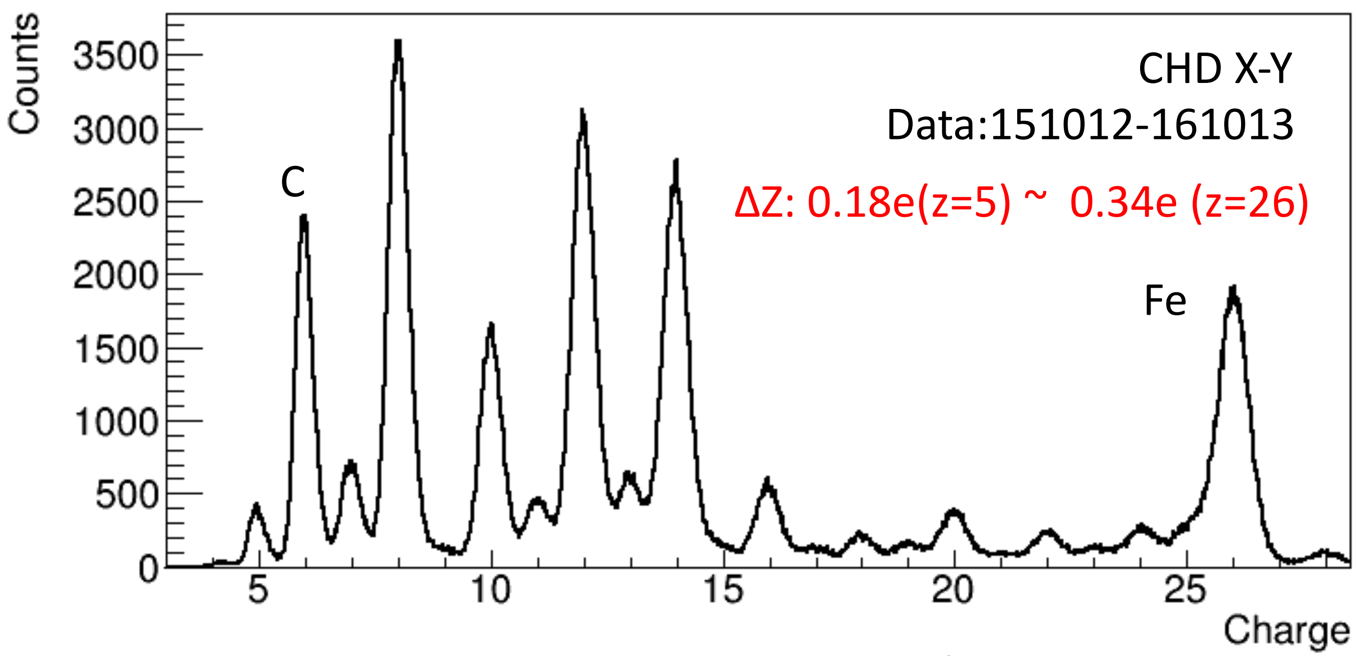
- Electron Analysis
  - High Energy Trigger using IMC-7&8+TASC-1: (A)+(B)+(C)+(D)
    - for e/p separation at high energy done mainly by using TASC
  - Low Energy Trigger using CHD+IMC+TASC-1: (A)+(B)
- Gamma-ray Analysis : (A) without the bottom layer of TASC
  - for precise rejection of charged particles at CHD
- Proton & Nuclei Analysis: (A) + (B)
  - for precise charge measurement at CHD
  - (C)+(D) for "mild" cut analysis is possible for protons
- Ultra Heavy Nuclei: Dedicated trigger using CHD and IMC (*see later)

Preliminary Nuclei Measurements – p , He and B to Fe –

*）小澤他、18aK21-2







A clear separation between p and He, and B-Fe can be seen from preliminary data analysis.

In following analysis, charge selection was carried out by a simple cut of charge region

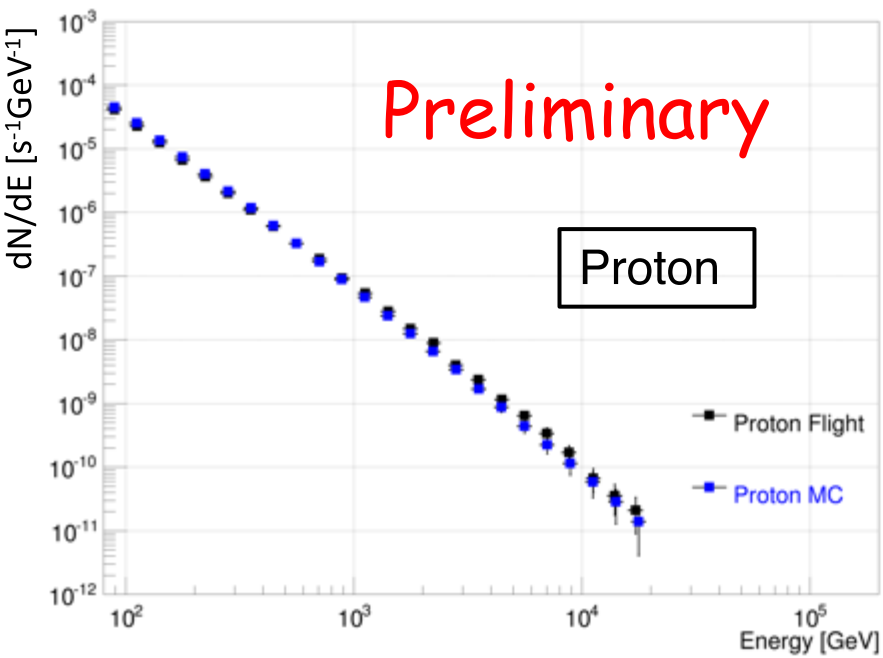
Preliminary TASC Energy Deposit Distribution: Proton and Helium

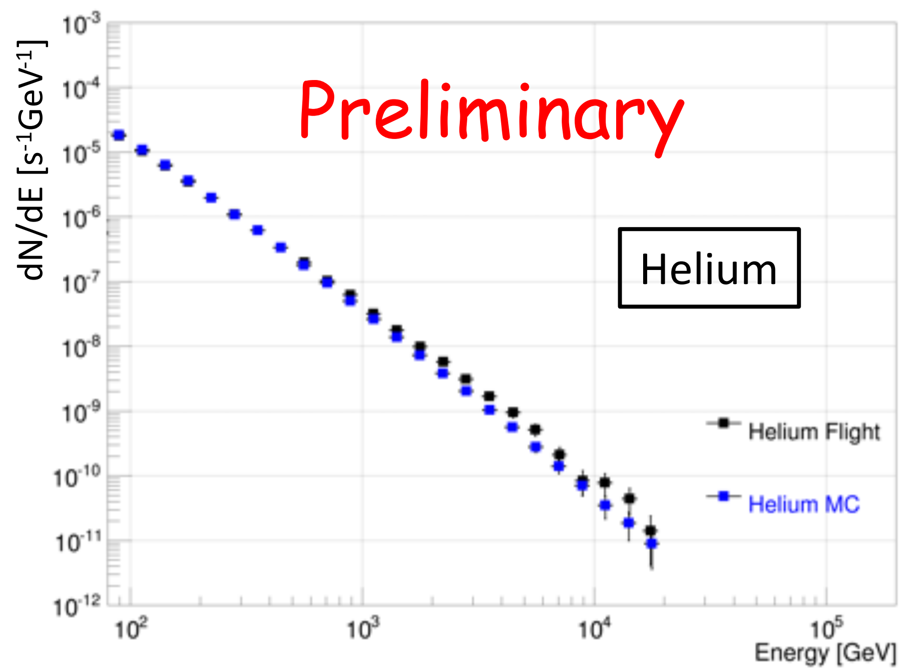
Flight Data

- Observation:
  2015.10.13-2017.01.31
- HE trigger (>10GeV)
- Topological cut (A) : 1.3×10^7
- Event selections p : 8.9×10^5
  He : 2.7×10^5

Simulation

- EPICS 9.167 with DPMJET3
- Differential power index assumed:
  -2.78 for Proton, -2,69 for Helium
  (similar with AMS-02)
- Isotropic incident (< 90°)
- Same cut and selections applied





*) They are VERY preliminary dN/dE distributions and the fluxes can be extracted only after estimation of primary energy and the energy unfolding.

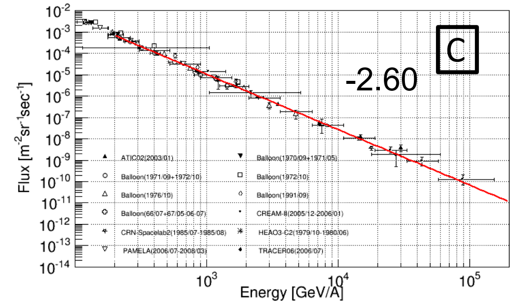
Preliminary TASC Energy Deposit Distribution : Carbon and Iron

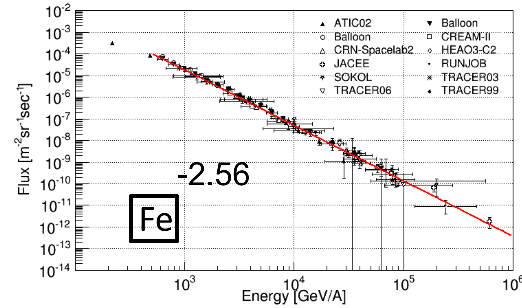
□ Flight Data

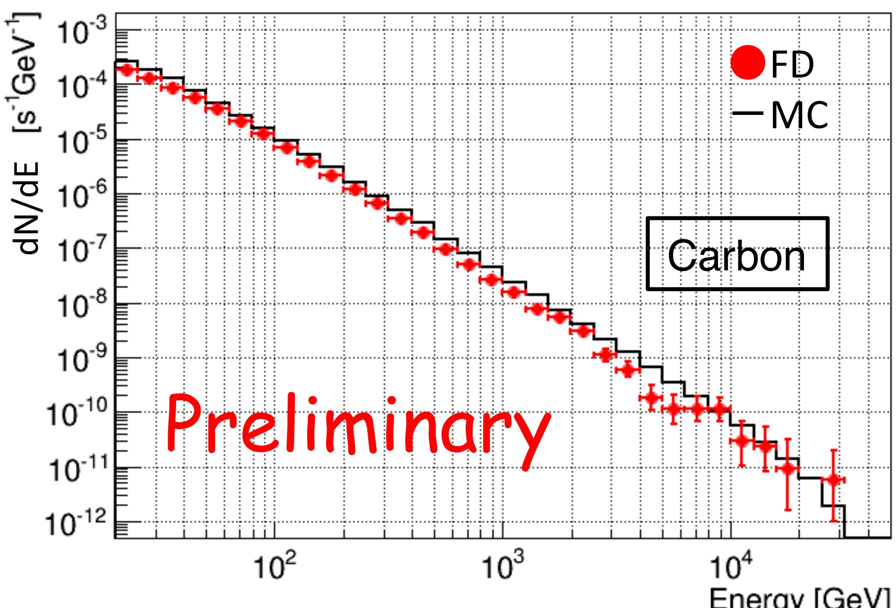
- Observation:
  2015.10.13-2017.10.12
- HE trigger (>10GeV)
- Topological cut (A+B)
- Event selections
  C : 1.8×10^5
  Fe : 2.3×10^5

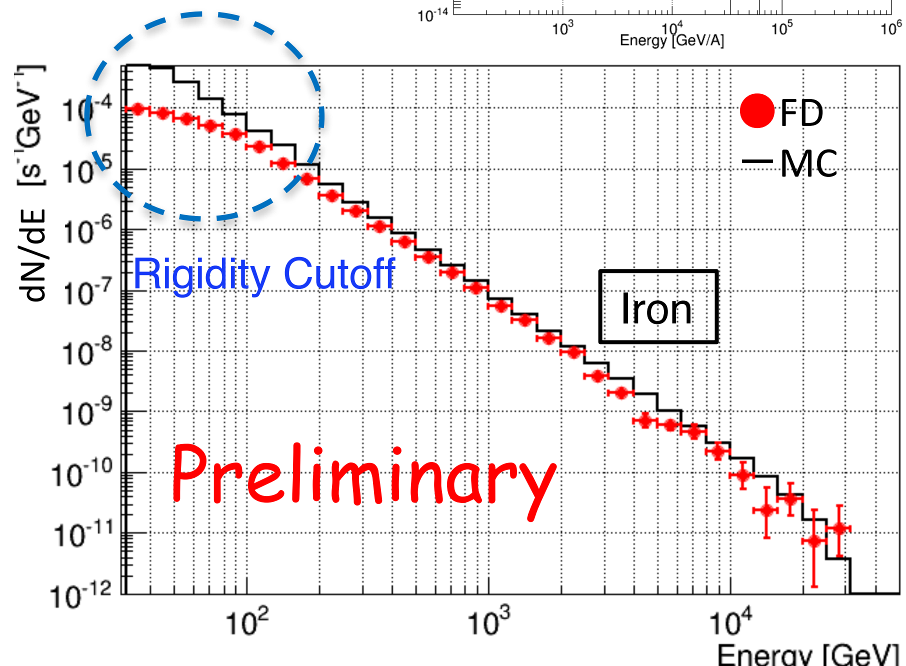
□ Simulation

- EPICS 9.167(C), 9.201(Fe) with DPMJET3
- Differential power index:
  -2.60 for C, -2.56 for Fe
- Isotropic incident (< 90°)
- Same cut and selections applied



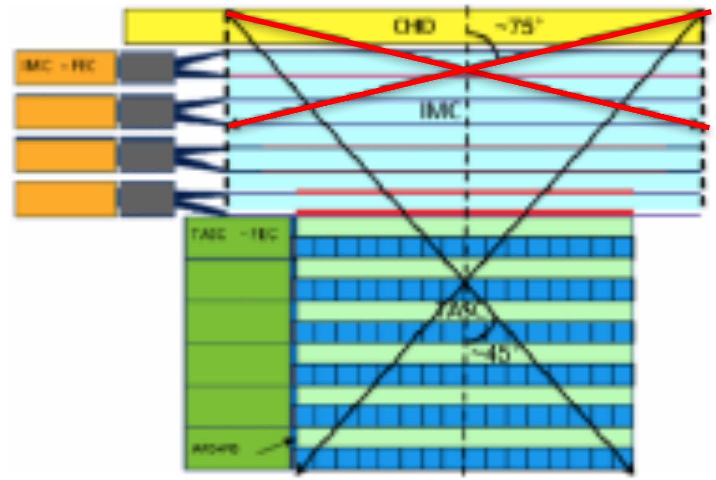






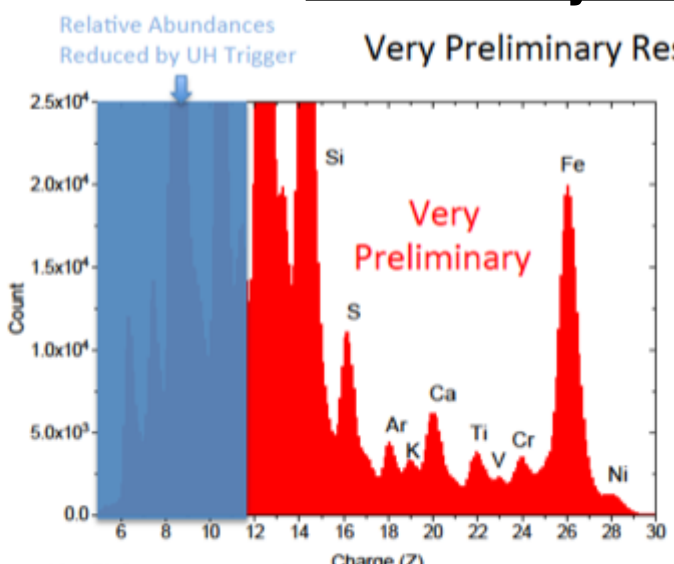
Ultra Heavy Cosmic Ray Analysis

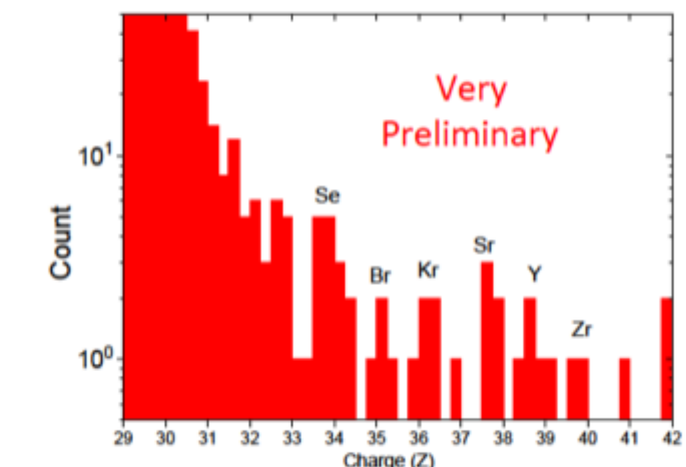
- CALET has a special UH CR trigger utilizing the CHD and the top 4 layers of the IMC
- Provides an expanded geometry factor of 4000 cm^{2}sr
- Analysis presented here uses data with UH trigger
- Relative abundances of lighter elements impacted as they only trigger at higher incidence angles



Preliminary Charge Histgrams

Very Preliminary Results from Only Two Months of Data





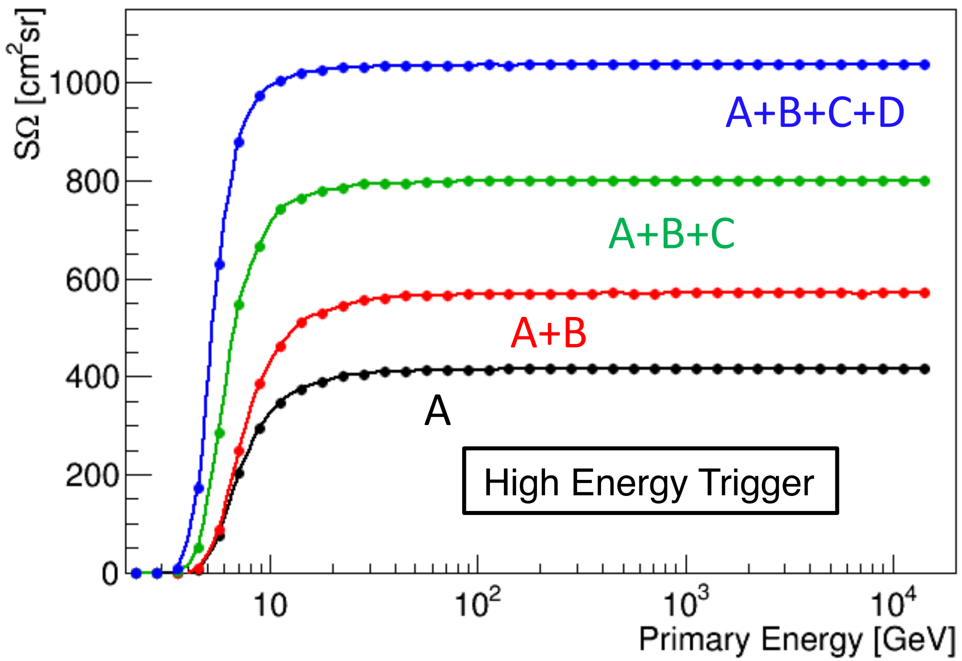
Electron Spectrum Analysis

- Geometry Condition: A+B => SΩ= 570.3 cm^2sr (55% for all acceptance)
- Live Time: 2015/10/13—2017/02/28 => T= 3.655 x 10^7 sec (1.16yr)
- Exposure: SΩT = 570.3 x 3.655 x 10^7 = 2.08 x 10^6 m^2sr sec

$$f\,[\mathrm{m^{-2}sr^{-1}s^{-1}GeV^{-1}}] = \frac{N}{\Delta E \cdot t \cdot S\Omega} \cdot \frac{1}{\epsilon} \cdot \delta$$

ε : efficiency
δ: contamination

Very flat acceptance over 10 GeV

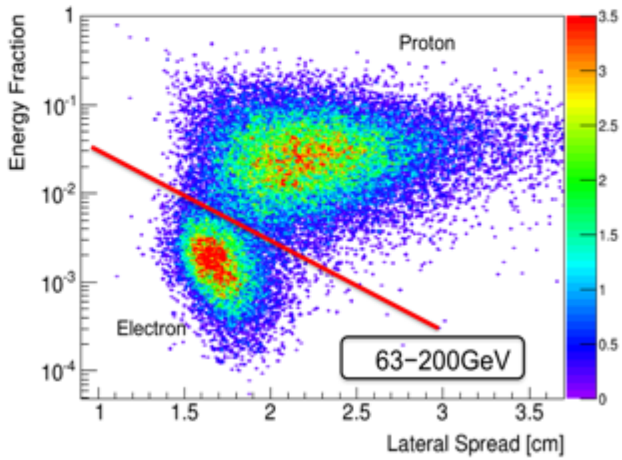


In addition,

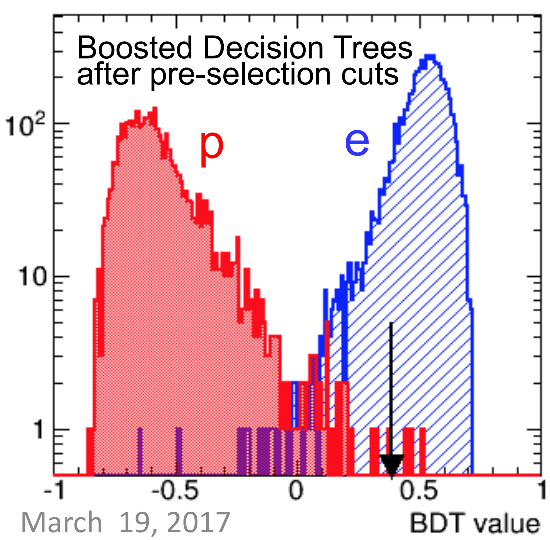
- Energy Scale Uncertainty:
  nearly 1 % @ > 20 GeV
- Energy Resolution:
  better than 3 % @ > 20 GeV
- Proton Contamination (Simple Cut):
  a few% ~ 10 % @ < 1 TeV

Differential Energy Distribution of the Electron-Candidates Observation for 505 days

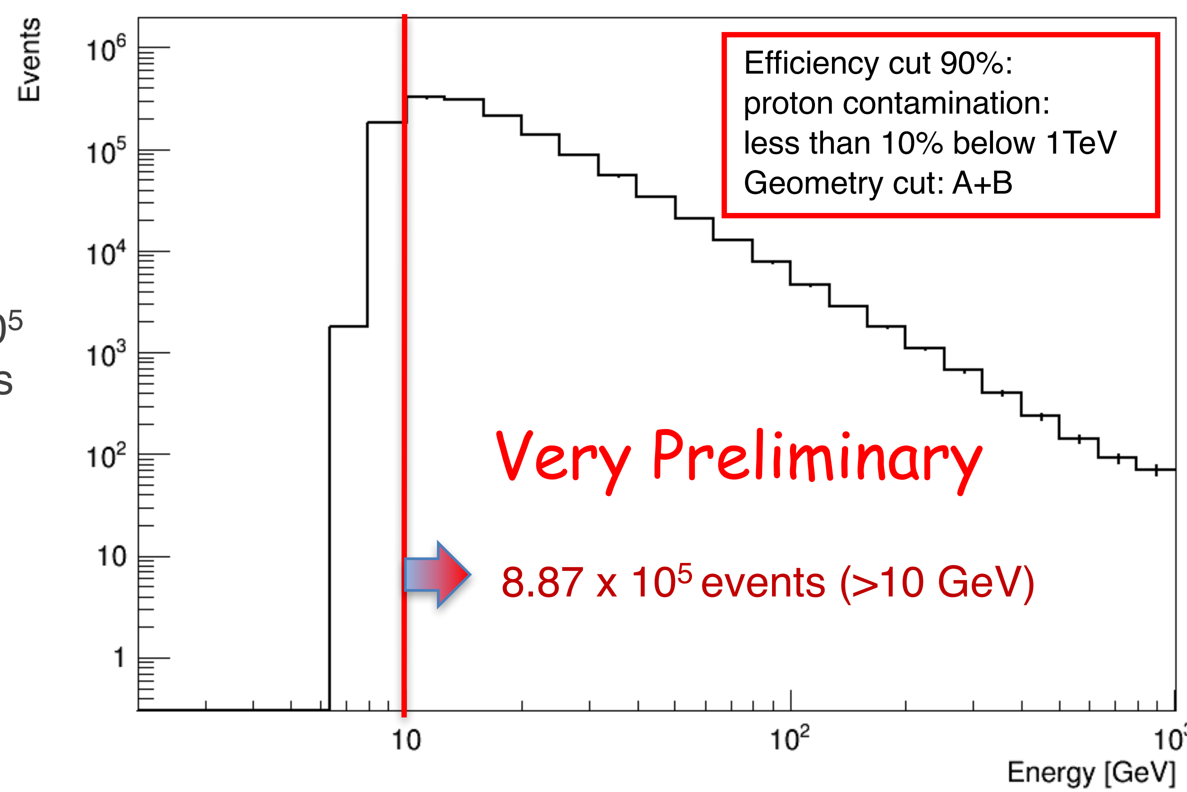
Observation: e/p separation after pre-selection cuts



Simulation : e/p at 1TeV ~1.3 x10^5 with ~90% efficiency for electrons



Differential energy distribution reconstructed by using the electron candidate events observed in 2015.10.13—2017.02.28

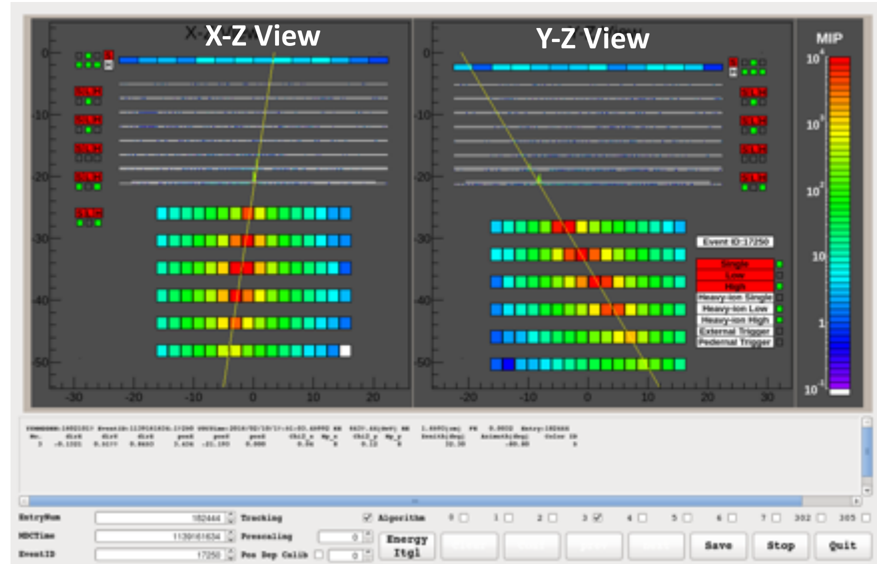


Energies are reconstructed after the calibrations.

Examples of Electron Candidates in TeV Region

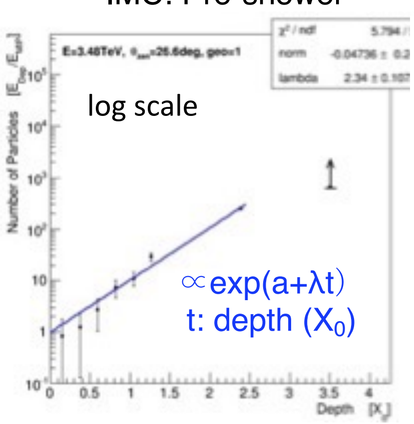
Energy: 3.62 TeV (θ=26.5°)

Energy: 6.75 TeV (θ=32.3°)

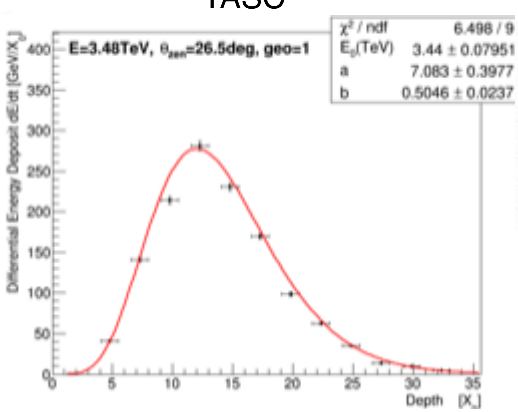


Longitudinal development of shower particles in IMC and TASC with fit of EM shower

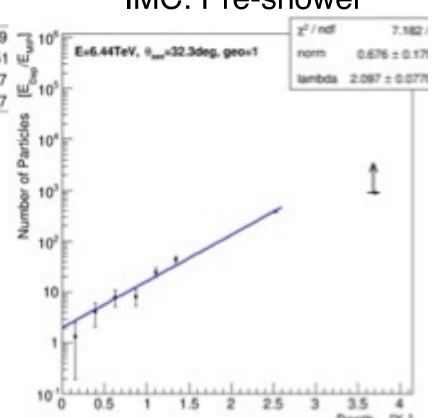
IMC: Pre-shower



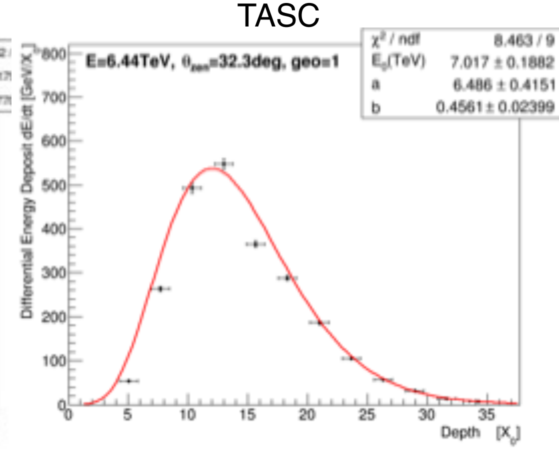
TASC



IMC: Pre-shower



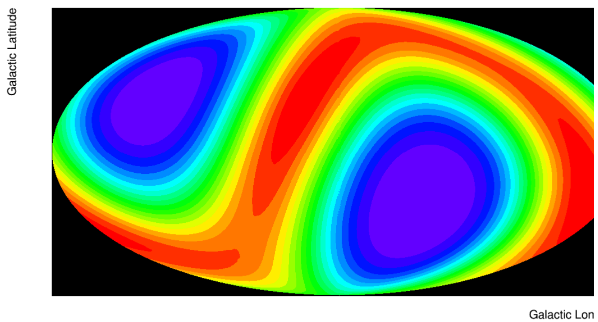
TASC



CALET γ–ray Sky in LE(>1GeV) Trigger

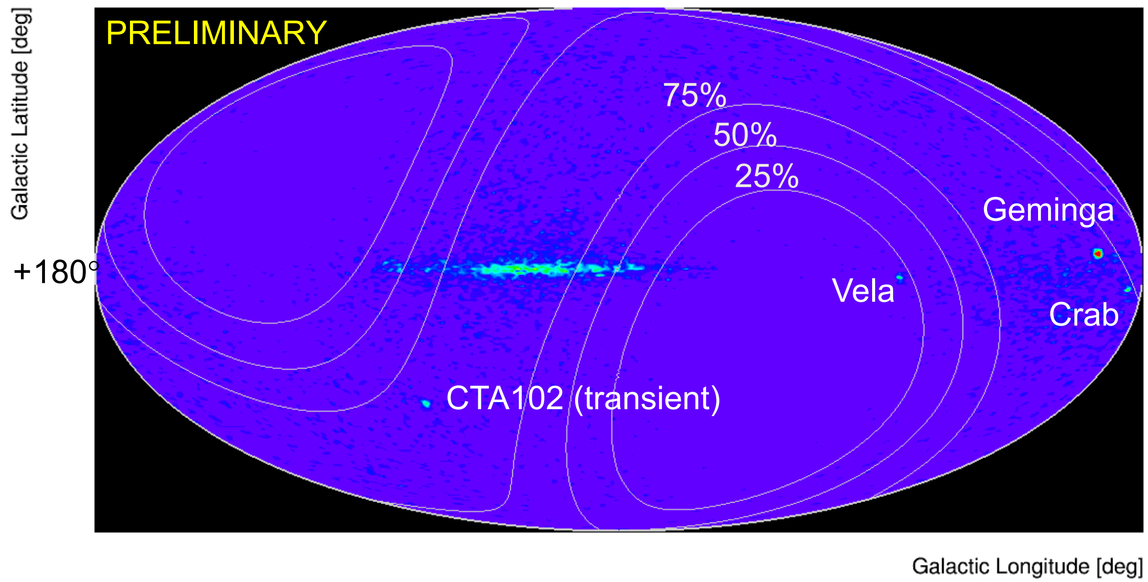
*) 浅岡他、18aK21-1

Exposore



Exposure is limited to low latitude region
=> ldeclinationl > 60 deg is hardly seen in LE gamma-ray trigger mode.

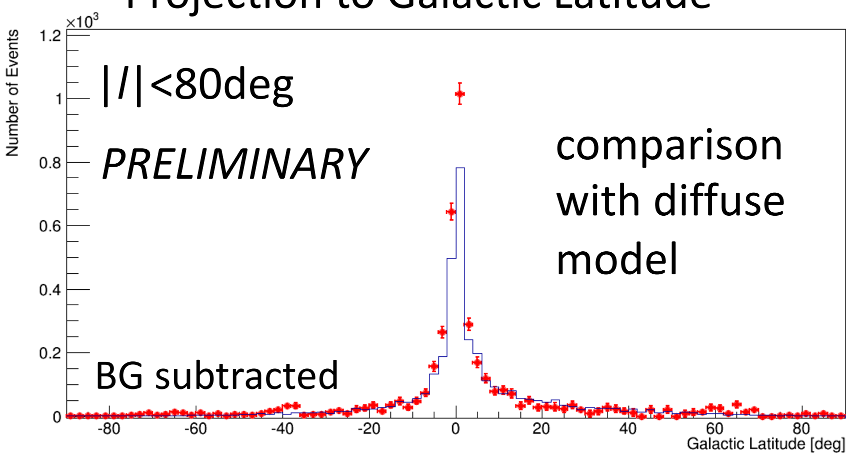
151013—170228 E>1GeV Galactic Coordinate



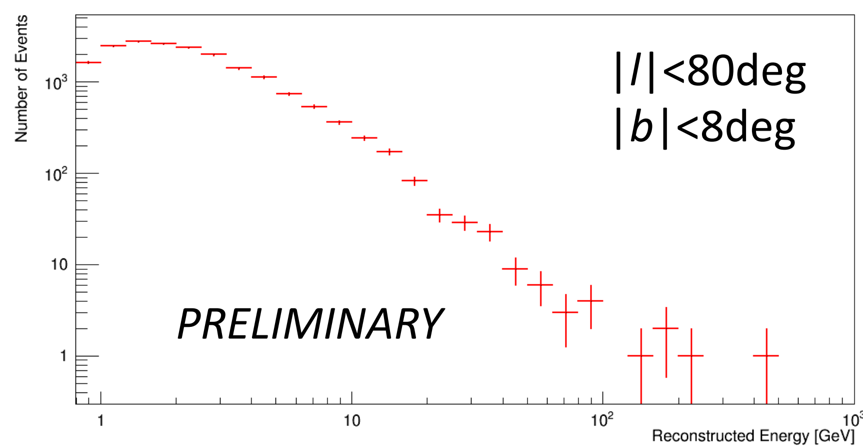
-180°

Geminga: ~200
Crab: ~100
Vela: ~100

Projection to Galactic Latitude



Galactic Diffuse Spectrum

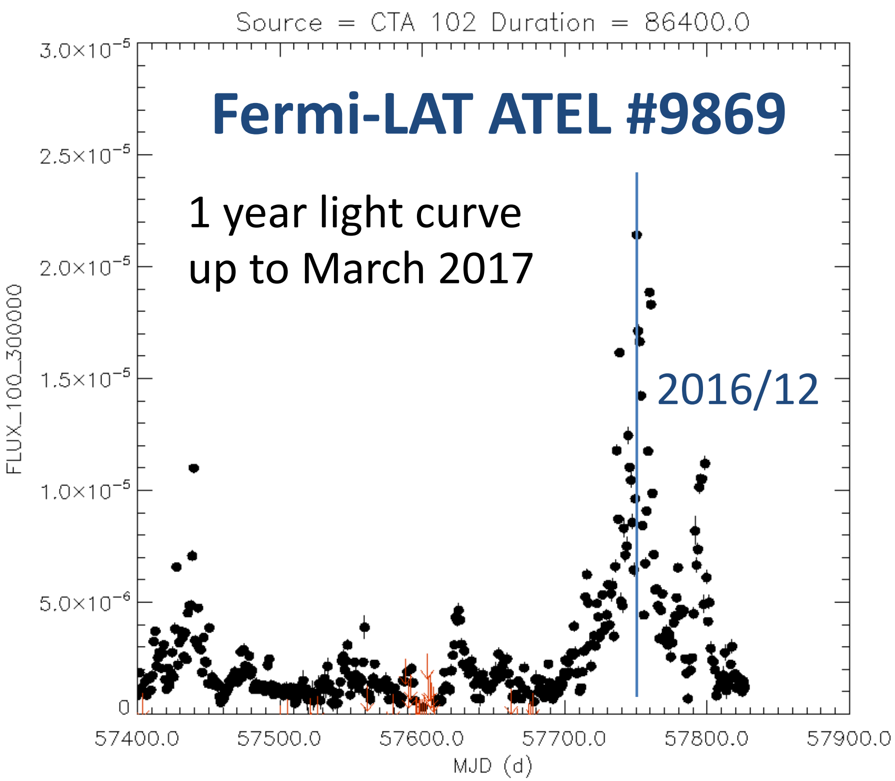


contribution from point sources is not included in the model

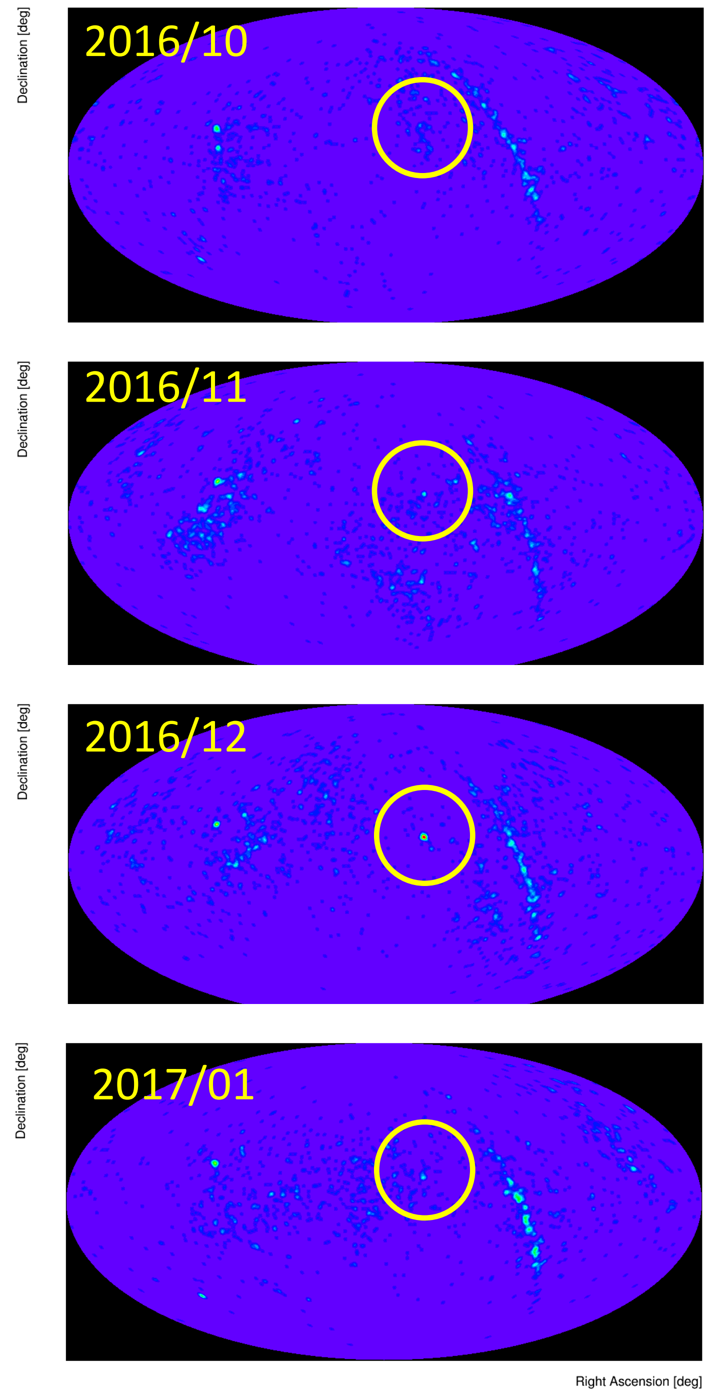
Strong GeV γ-ray Activity from blazar CTA 102

reported to ATEL by AGILE, Fermi, DAMPE in GeV

⇒ Also detected by CALET

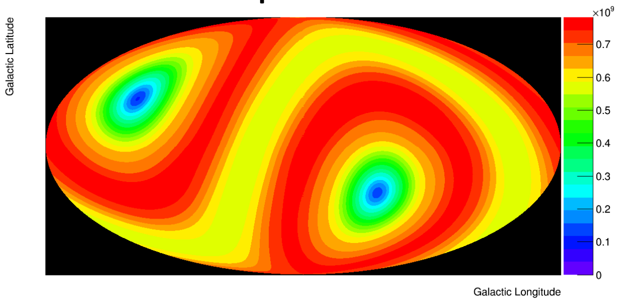


https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/source/CTA_102



CALET γ–ray Sky in HE (>10GeV) Trigger

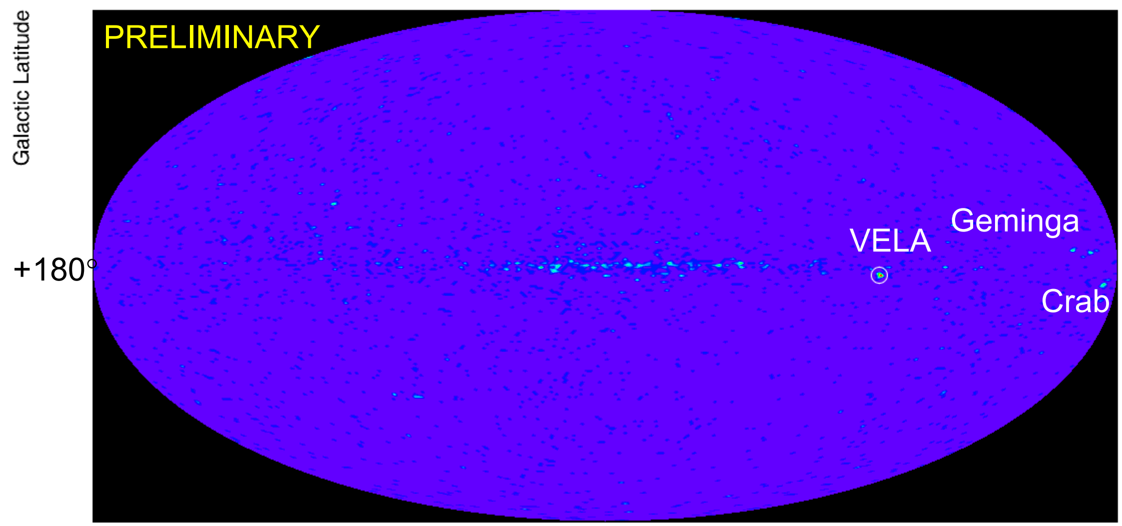
Exposure



HE trigger is always ON
=> Exposure determined by the ISS orbit and FOV is more uniform than LE trigger.

Galactic Coordinate

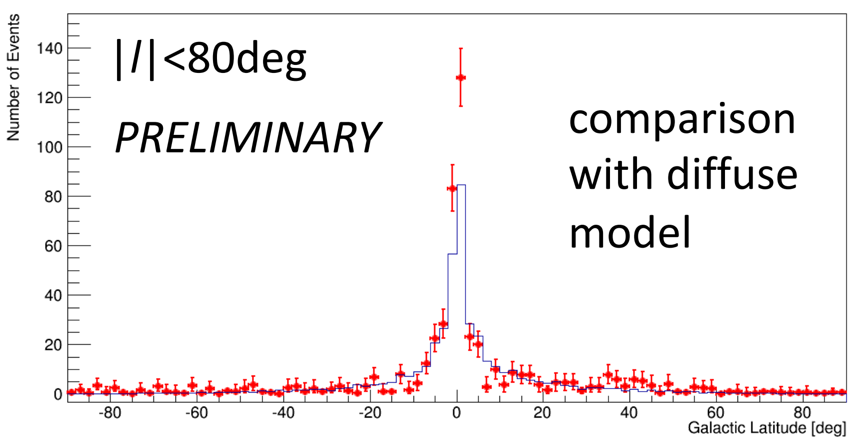
151013—170228 E>10GeV



Geminga: ~10
Crab: ~20
Vela: ~20

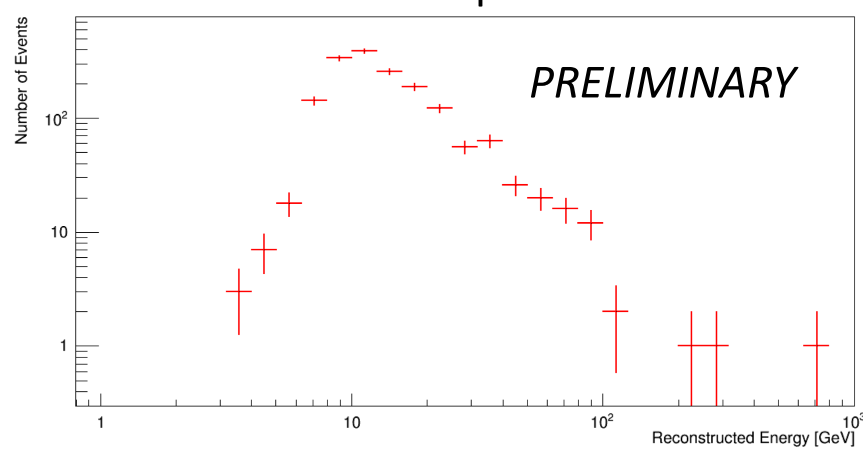
Vela, Crab and Geminga are identified.

Projection to Galactic Latitude



comparison with diffuse model

Diffuse Spectrum



contribution from point sources is not included in the model

CALET UPPER LIMITS ON X-RAY AND GAMMA-RAY COUNTERPARTS OF GW 151226

http://arxiv.org/abs/1607.00233v2: accepted by Astrophysical Journal Letters

The CGBM covered 32.5% and 49.1% of the GW 151226 sky localization probability in the 7 keV - 1 MeV and 40 keV - 20 MeV bands respectively. We place a 90% upper limit of 2×10^{-7} erg cm^{-2} s^{-1} in the 1 - 100 GeV band where CAL reaches 15% of the integrated LIGO probability (~1.1 sr). The CGBM 7 σ upper limits are 1.0×10^{-6} erg cm^{-2} s^{-1} (7-500 keV) and 1.8×10^{-6} erg cm^{-2} s^{-1} (50-1000 keV) for one second exposure. Those upper limits correspond to the luminosity of 3-5 $\times 10^{49}$ erg s^{-1} which is significantly lower than typical short GRBs.

CGBM light curve at a moment of the GW151226 event

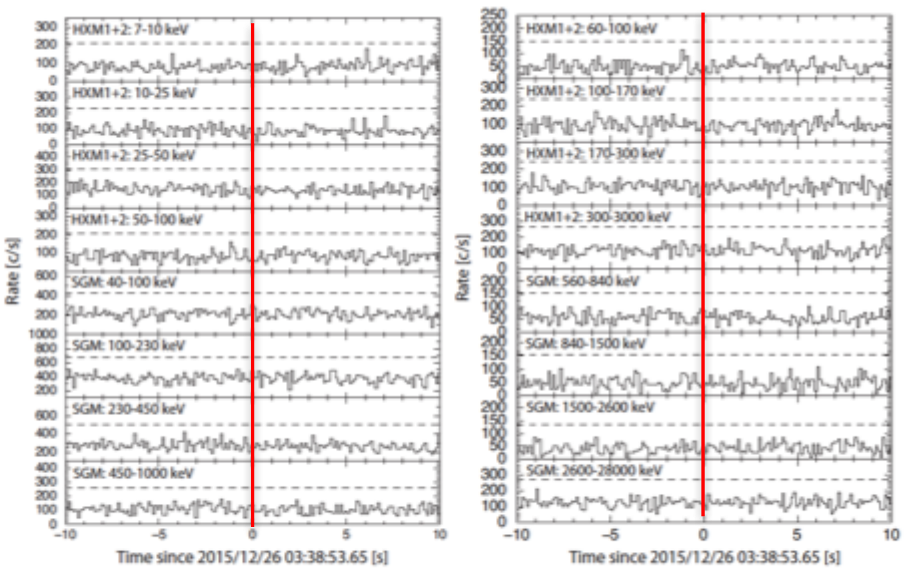


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

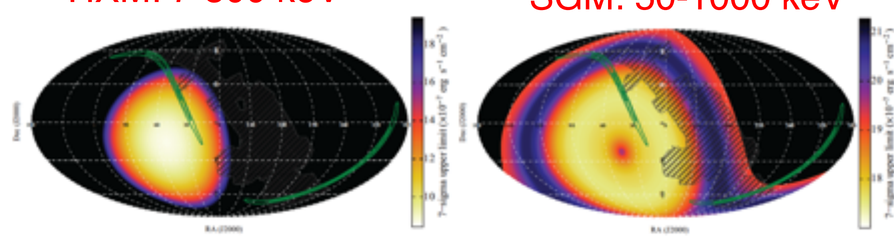


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating th upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV fo SGM. The GW 151226 probability map is shown in green contours. The shadow of ISS is shown in black hatches.

Calorimeter: 1-100 GeV

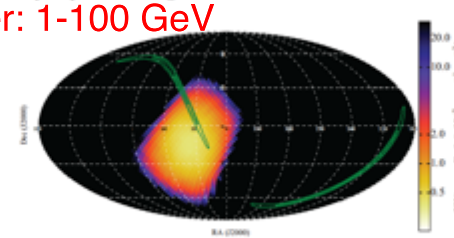


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of − is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

まとめと展望

- CALETはTeV領域に及ぶ電子・ガンマ線観測により近傍加速源と暗黒物質の探索を行うほか、陽子・原子核の観測を1000TeV領域まで実施して宇宙線の加速・伝播機構の 包括的な解明を行う。さらに、太陽変動やガンマ線バーストの研究を行う。
- CALET は、2015年８月１９日に種子島宇宙センターからHTV5号機に搭載して打ち上げられ、現在まで国際宇宙ステーション日本実験棟「きぼう」の船外実験プラットフォーム＃９ポートにおいて、所期の性能を発揮して順調に観測が実施されている。
- 現在早稲田大学CAET Operations Center (WCOC)において、つくば宇宙センター経由でデータ送受信を実施しており、ガンマ線バーストをふくむ軌道上運用が24時間体制で実施されている。今後は、２年間の観測後にフルサクセスの成功基準達成審査をうけ、５年間の観測を実現する予定である。
- 現在までに、すでにRelativistic Electron Participation (REP)の観測や、LIGOが検出した重力波イベントGW151226の電磁波同時観測で成果を上げている。
- 高エネルギー宇宙線の観測においてデータが順調に蓄積され、データ解析も国際チームにより進展しており、電子、ガンマ線及び原子核観測での初期成果が得られている。 今後は、5年間の観測で期待される現在の約１０倍の統計量の精密なデータ解析により、科学観測目的の達成を目指す。

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